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NORTHROP AIRCRAFT, INC.

HAWTHORNE, CALIFORNIA

COMPARISON BETWEEN AIR TEMPERATURES AS MEASURED BY VARIOUS SHIELDED TEST THERMOCOUPLES AND A REFERENCE DOUBLE-SHIELDED ASPIRATED THERMOCOUPLE

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ABSTRACT

A comparison is made between air temperatures as measured by various single and multiple-shield test thermocouples and by a reference double-shielded aspirated thermocouple. The test specimen and standard are centered, three inches apart, in the 78 in. x [illegible] in. floor of a [illegible] in. high test chamber the ceiling of which is adjusted for temperatures of 500°F, 700°F, and 900°F. Air enters the chamber at approximately 70°F, reaching temperatures in the range 80°F - 200°F at the center section, under turbulent flow conditions of from 0 to 48 lb - min^{-1} - ft^{-2}. Specimens currently in use on aircraft installations are found to record air temperatures considerably in excess of those registered by the reference instrument. Furthermore, indications are that some sort of quality control should be exercised to assure production of instruments uniform in performance. Altogether, thirteen different instruments were tested. An aluminum double-shield specimen (3 in. long outer - 2 in. long inner-shield), having an outside shield diameter of 1 in., was finally evolved, and it recorded temperatures in much closer agreement with the reference thermocouple than any of the other instruments considered. The sources of error in this type of temperature measurement are also briefly discussed.

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NOMENCLATURE

T	=	Total Temperature
T_g	=	Effective Gas Temperature
L	=	Length
h	=	Film Coefficient
k	=	Thermal Conductivity
S	=	Surface Area
A	=	Cross-Sectional Area
ϵ	=	Emissivity
σ	=	Stephan-Boltzmann Constant
M	=	Mach Number
γ	=	Ratio of Specific Heats, C_p/C_v
r	=	Recovery Factor
F_a, F'_a	=	Geometric Factors for Radiation

Subscripts

c	=	conduction, convection (see context)
i	=	indicated

Subscripts (Cont'd)

w = wall

R = radiation

s = shield

o = static

r = recovery, radiation (see context)

p = probe

STATEMENT OF PROBLEM

There is reason to believe that thermocouples currently in use on missile and aircraft installations, for measuring air temperatures (in the approximate range 70°F - 200°F) in the vicinity of radiant heat sources, are not optimum from the standpoint of accuracy, uniformity, complexity, and structural properties. Specifically, thermocouples presently used extensively on B-62 test stand programs and on F-89 engine bay cooling programs are suspected of being seriously in error and diverse in performance.

The objectives of the present test are twofold: (1) to compare the air temperatures measured by thermocouples now in use with temperatures measured by a reference "standard" taken to be measuring "true" air temperature; (2) to compare the readings of several varities of thermocouples with readings obtained from the specimens above, and with the standard, in an effort to ascertain the optimum instrument.

The emphasis in the present investigation, then, is on comparison, in order to rank the specimens in order of increasing accuracy, where accuracy is defined as the difference between specimen reading and standard reading for a particular operating condition, or "fix". It was anticipated that the data gathered in compliance with the first-named objective above could be used for correcting the temperature readings of thermocouples presently in use; however, such a procedure should be used with reservation, and only when it is impractical to install more accurate thermocouples and repeat a given test.

Once an optimum instrument is chosen, the calibration of a few random samples of the specimen will give a measure of the quality control.

In conformity with the objectives, the following specimens were tested:

(1) and (2): Two sample 1 in. long, single-shield, specimens (Figure 4B)

(3): One 2 in. long, single-shield, specimen (Figure 4B)

(4): One 2 in. long, double-shield, specimen (Figure 4C)

(5): One 2 in. long, triple-shield, specimen (Figure 4D)

(6): One Revere Corporation thermocouple - a 1-1/4 in. long triple shield specimen with encapsulated junction. (Reference Revere TK2702P Modification by NAI ETD #702369, pg. 2, item 12)

(7): One bare thermocouple (Photo pg. 72)

(8) and (9): Two sample "umbrella" - shield specimens (Figure 4A) currently in use on F-89 engine bay cooling programs.

The shield material is ~~stainless~~-steel tubing; the elements are Iron-Constantan with silver-soldered junctions. Photographs of the specimens are shown on pg.71 - 74.

As the test progressed, it became evident that some room was left for improvement; accordingly, the following additional specimens were designed and tested:

(10): One sample 2 in. x 2 in. flat umbrella-shield specimen (Figure 4E)

(11): Same as (10) but with insulation and aluminum foil over top of shield.

(12): One sample 2 in. long inner-3 in. long outer-shield specimen (Figure 4G).

(13): Same as (12) but with Venturi-shaped inner shield (Figure 4F)

The temperature-sensing element is the same as for the samples (1) through (9) above, but the shield material is aluminum. Photographs of the specimens tested are shown on pages 71 - 74.

The temperatures measured by these specimens were compared to that measured by a double-shielded aspirated thermocouple which was used as a standard. The test chamber used (Figure 5 and photos pg. 70) was dimensioned so as to simulate conditions extant in the engine bay, and several representative flow and hot wall conditions were considered.

CONCLUSIONS

Strictly speaking, the performance of the various specimens is limited to the present experimental configuration, (Reference 10), but there is little reason to believe that the order of increasing accuracy discovered here would actually be reversed for a different test chamber geometry. Furthermore, while the inaccuracy is not the same function of flow and hot wall conditions for each specimen, the overall test results suggest the following ranking, in order of increasing accuracy (numbering refers to that assigned to specimens under "Statement of Problem", above):

$$(9) < (2) < (7) < (1) < (8) < (6) \cong (3) \cong (4) < (10) < (11) < (13) < (5) < (12)$$

The actual test results are shown in the graphs of Figures 2.

Two striking results are immediately apparent from the above arrangement: (a) The difference in the performance of samples of, presumably, the same specimen, e.g., thermocouples (1) and (2) and, particularly, (8) and (9); (b) The approximately equal performance of such geometrically dissimilar specimens as (3), (4), and (6).

As was suspected, the thermocouples now in use are reading much too high, and the data of Figure 2F, or

Table 1 which shows the range of applicability (specimen-measured air temperature) should be used to "correct" the readings obtained in the past with these instruments.

The results (Figures 2H) from one of the newly designed instruments, specimen number (12), with the 3 in. long outer, 2 in. long inner, aluminum shields (Figure 4G) are very encouraging. This instrument functions every bit as well as the more cumbersome standard in the presence of a hot wall radiant source as high as 900°F when the air temperature is in the vicinity of 70° - 90°F, and the flow is in the vicinity of 48 lb - min^{-1} ft^{-2}. For a somewhat lower flow, 19 lb - min^{-1} - ft^{-2}, this instrument measured 10°F above the standard for a hot wall of 900°F and air temperature in the vicinity of 80° - 100°F. At still lower flows (9.6 lb - min^{-1} - ft^{-2}) the error is somewhat greater, the specimen reading 14°F above the standard for both a 700°F and a 900°F hot wall. For zero main air flow this instrument reads 85°F above the standard for a hot wall at 900°F, 49°F above the standard for a hot wall at 700°F, and 27°F above the standard for a 500°F hot wall. Even so, it will be noted that this double-shield specimen performs considerably better than any other specimen tested for all flow and hot wall conditions considered (Cf Figures 2D and H). It is interesting to note that whereas the slope (interpreted as the rate of change of "error" with hot wall temperature) of most of the curves increases with increasing hot wall temperature, in the case of both this double-shield and the triple-shield specimens it decreases with increasing hot wall temperature in the moderate to low flow ranges. The effect of flow orientation on this double-shield instrument is shown on Figures 3Q, R, S and T.

The consideration of an "umbrella" shield thermocouple, which a perfunctory thermodynamic analysis indicates to be subject to great error, is justified in the desire for a device that is insensitive to flow orientation. The umbrella-shield specimens are indeed less sensitive to the air flow vector, but the steeper slope of the curves, signifying greater intrinsic error, exaggerates any differences as shown on Figures 3. The flat umbrella-shield thermocouples (Figure 4E) were designed in an effort to overcome the effect of shield curvature, which modifies the air flow pattern over the junction as orientation is changed. An additional advantage of the flat shield is that it precludes the possibility of radiation being focused on the junction by the shield. The instrument designed, particularly the insulated-shield specimen, ~~compares~~ favorably (Figure 2F) with the better of the curved-umbrella-shield specimens (Spec. 8) now in use and has the added advantage of being less sensitive to flow orientation (Figures 3 M, N, O, and P) and of requiring less care in manufacture. However, the decreased flow-orientation sensitivity is not felt to be of sufficient significance to warrant this instrument's use (especially in view of its greater inherent inaccuracy) in deference to the completely shielded instrument.

Thermodynamic considerations indicate that the various specimens should read "truer" at high flows and such is indeed the case. Figure 1A, for example, indicates that it would be fairly safe to assume that above about 100 lb. min^{-1} - ft^{-2}, and a hot wall radiant source at 900°F, the deviations among the various specimens, as well as the deviations of each specimen from "true" air temperature, will not be significant. Figures 1 are included merely to indicate the nature of the dependence of temperature reading on flow and do not give a true picture of the inaccuracy. The points along a given ordinate represent different "fixes", e.g., at 12 lb - min^{-1} ft^2 and a 900°F hot wall the reading of the curved-umbrella specimen is referred to the upper curve of the standard whereas the 2 in. single-shield specimen refers to the lower curve (Table 1). For the sake of clarity not all of the specimens are shown on these graphs.

Since the hot wall could not be maintained at a uniform temperature throughout, the temperatures near the center of the hot wall were adjusted to 500°, 700°, and 900°F for the various runs (Reference 10). Some typical temperature distributions are shown in Table 1.

A calibration test was run by simultaneously immersing all the specimens in a bath of Dow Corning #710 Fluid. At bath temperatures of 70°F, 150°F, and 212°F (as measured by a mercury-in-glass thermometer) all the specimens read within one or two degrees of one another, and no specimen gave a temperature differing by more than 3° from that indicated by the thermometer.

CRITICAL CONDITIONS

The following "fixes" were used as being representative of conditions for which application of the thermocouple is contemplated:

48 lb-min^{-1} ft^{-2}; turbulent flow; hot wall 500°, 700°F, and 900°F (1)
19 " " " " " " " " "
9.6 " " " " " " " " "
0 flow; hot wall 500°, 700°, and 900°F

The aspirated air flows for the standard (reference) thermocouple are as follows:

20 lb-hr^{-1} for 900°F hot wall, zero flow
18 " " 700°F " " " "
16 " " 500°F " " " "
14 " with flow, for all hot wall temperatures.

Under these conditions, the standard was taken to be measuring "true" air temperature.

Note (1) As mentioned under "conclusion" above, these temperatures refer to the center of the hot wall, immediately above the specimen and standard.

ASSUMPTIONS

The paramount assumption in the present investigation is that the reference standard, which is a double-shield aspirated thermocouple (Figure 6) gives a true indication of the air temperature.

The idea of an aspirated thermocouple is an old one, dating back as early as 1887 in a model used by R. Assman (Reference 1); it soon became an established means of temperature measurement in Germany, and, at one time, imported models sold for $300.00 in this country.

The instrument used in the present test is quite similar to Assman's early model and operates on the same principle (Reference 5). Thermocouples in the vicinity of radiant sources will be at a higher temperature than the surrounding air, provided that the air is at a lower temperature than the radiant source, due to the radiation incident on the thermocouple (1). In the converse case, where hot air is flowing through a cool duct, the thermocouple will register a lower temperature than that of the air since it looses heat, via radiation, to the cooler walls (References 2 and 3). By increasing the

Note (1) For all practical purposes, air may be considered transparent to this radiation; it therefore becomes heated by convection from the hot wall.

velocity of the air over the junction, the Nusselt modulus, and hence the rate of convective heat transfer, is increased so that the temperature of the junction approaches the air temperature. Each increment in air velocity will result in a decrement in the temperature registered by the thermocouple until a point is reached at which further increase in flow leads to no change in temperature. This point, then, may be taken as the definition of "true" air temperature.

It should be noted, however, that if the temperature registered by the thermocouple is plotted versus the aspirated air flow a curve resembling one branch of hyperbola is obtained. In other words, the point at which a further increase in air flow leads to no further decrease in measured temperature may not be the lowest temperature the instrument could measure. Thus, whereas 2 $lb\text{-}hr^{-1}$ increments may be quite satisfactory near the "knee" of the curve, as the asymptote is approached a further decrease of 2 or 3 degrees might be obtained after three or four additional 2 $lb\text{-}hr^{-1}$ increments.

The reason for belaboring the above point is that the "good" specimen was so good it exceeded the accuracy of the standard, (under the present experimental conditions) reading 3°F lower at one fix (48 $lb\text{-}min^{-1} - ft^{-2}$; 900°F hot wall.) This does not militate against the utility of the present investigation whose primary objective was the choice of an optimum instrument from among a group of specimens whose performances were compared. For this reason, the curves (Figure 2H) are not extended below the abscissa. In other words, having chosen a standard, it would be incompatible with the thermodynamics of the present situation (radiant source and cooler air) to draw a graph indicating that a certain number of degrees are to be added to the reading of the specimen, for as noted above, it is possible for the aspirated thermocouple to read slightly above the true air temperature because of the asymptotic nature of its temperature vs air flow curve.

An additional assumption, though it would seem from symmetry considerations to be a very reasonable one, is that the specimen and the aspirated thermocouple each measure the same thing, i.e., air at the same temperature and under roughly equal flow conditions. Furthermore, the specimen and standard are regarded as being in, essentially, the same environment from a radiation and over-all flow pattern standpoint.

RECOMMENDATIONS

It is recommended that the use of all umbrella-shield thermocouples be discontinued. Temperatures formerly recorded by these instruments and used in current analyses should be corrected by interpolating between the two samples tested (Figure 2F), though the use of such a correction procedure is discouraged as noted in Reference (3).

Use of the 2 in. long inner, 3 in. long outer aluminum-shield specimen (Figure 4G) is recommended; these devices should be used for instrumentation requiring the measurement of air temperatures in the vicinity of radiant heat sources and air flows in the range covered by these tests.

Three or four random samples should be chosen from a group of these specimens in order to obtain a measure of the dispersion, or scatter, in their accuracy. It is essential that reasonable care be exercised to assure a uniform product as attested to by the wide discrepancies noted above between samples of the same specimen. Whether a correction, using graphs such as Figure 2H, is to be applied to the readings obtained with this instrument may be left to the discretion of the engineer in charge. It is believed, however, that the accuracy of this type of instrument is adequate for the tests and heat transfer analyses conducted on engine bays, although it may be desirable to apply a correction for flow orientation, using the curves of Figures 3Q, 3R, 3S and 3T.

ANALYSIS

Reports dealing with the measurement of gas temperatures are legion (Reference 4). However, no previous work in the nature of the present study seems to have been undertaken.

As noted in all these reports, the exact measurement of air temperatures is hindered by the many inaccuracies inherent in this type of measurement. These errors, while they cannot be eliminated in their entirety, may, however, be rendered much less effective (References 6 and 7). Among the more influential factors contributing to the error of measurement the following may be singled out as deserving special consideration:

<u>Conduction Error:</u> If the thermocouple is attached to a surface at a lower (or higher) temperature than the air stream, heat will be conducted away from (or to) the junction along the thermocouple leads to (or from) the cooler (or hotter) surface with the result that the thermocouple junction will read too high (or too low). This effect can be reduced (a) by decreasing the wire diameter(1)

Note (1): Other things being equal, a reduction from 8 Ga to 22 Ga in the leads of a bare thermocouple resulted in an increase in measured air temperature from 1850°F to 1950°F (the latter being closer to "true" air temperature) - Ref. 6, Fig. 7, p. 815.

(b) by insulating the wire from the point of attachment, and (c) by exposing a section of the bare wire, leading away from the junction, to the air stream; the latter procedure helps to maintain the junction at air temperature by keeping the conduction path leading from the junction near air temperature. The conduction error may be evaluated from

$$(T_i - T)_c = \frac{T_W - T}{\cosh (mL)} \qquad (1)$$

where T = Total temperature (Theoretical value)

T_i = Indicated total temperature ($T_i > T$)

T_W = Wall temperature ($T_W > T_i > T$)

L = Immersed length of probe.

and,

$$m = \sqrt{\frac{hS}{kA}} \qquad (1a)$$

where h = Surface coefficient ("Film coefficient") of heat transfer.

k = Thermal conductivity of probe material.

S = Surface Area of probe.

A = Cross-sectional area of probe.

From Equation (1) it follows that the conduction error is directly proportional to the difference between the temperature of the gas and the temperature of the wall in which the probe is mounted and inversely proportional to the length of the probe. Furthermore, it is seen that the error becomes smaller with increasing m (Equation 1a), i.e., when the surface coefficient of heat transfer is large, and when the thermal conductivity and cross-sectional area of the probe are small.

Radiation Error: Thermocouples, in the presence of radiant sources at a temperature above that of the surrounding air, receive heat directly from the radiating source (air being transparent to this radiation) and hence will be at a temperature above that of the air. Two means of combating this problem are: (a) Shielding the junction from the radiant source using one or more shields (b) Increasing the velocity of the air over the junction which has the effect of increasing the Reynolds' modulus which, at a given temperature (constant Prandtl modulus), increases the Nusselt modulus; thus more heat is convected away from the junction (or towards the junction if the latter happens to be below air temperature) with the result that it approximates the air temperature more closely. The thermometric error, $(T_i - T)_R$, due to radiative heat exchange between the sensing element and the surroundings, for a temperature probe with one radiation shield and a surface area of the sensing element small compared with the surface area of the shield, is given by

$$(T_i - T)_R = \frac{\sigma \epsilon}{h}\left[\left(\frac{T_s}{100}\right)^4 - \left(\frac{T_i}{100}\right)^4\right] \qquad (2)$$

where σ = Stephan-Boltzmann constant

ϵ = Emissivity of the temperature sensing element

h = Surface coefficient of heat transfer from the sensing element to the gas.

T, T_i, and T_s = The total temperature of the gas, the indicated temperature of the probe, and the temperature of the radiation shield, respectively.

Equation (2) shows that, in order to reduce the radiation error, the emissivity of the sensing element should be low (this is one reason for silver-soldering the junction), that the surface coefficient of heat transfer should be large, and that the temperature difference between the element and the radiation shield should be small; this is sometimes accomplished by surrounding the inner shield with one or more outer shields. Interposing one shield between a radiating body and its surroundings will reduce the radiation by one-half, or to $1/(n + 1)$ of the value without shields, for approximately stagnant air (Reference 2) and to about $1/2^n$ with flowing air (Reference 3), where n is the number of shields.

Impact and Friction Error: These effects cause the thermocouple to read too high. Friction, in the boundary layer adjacent to the junction, will cause the boundary layer to assume a temperature somewhat higher than free stream and the compressibility effects will do likewise. The compressibility effects are accounted for in the expression

$$T/T_o = 1 + \frac{(\gamma - 1)}{2} M^2 \qquad (3)$$

where M = Mach number

γ = Ratio of specific heats, C_p/C_v

T = Total temperature

T_o = Static temperature

The fact that the gas at the probe surface has a temperature greater than free stream temperature, T_o, (and lower than T) is taken into account by defining a "recovery factor,"

$$r = (T_r - T_o)/(T - T_o), \qquad (4)$$

where $T_o < T_r < T$ and T_r is called the recovery temperature. As seen by Eq. (4), r is a measure of the fraction of the difference between T and T_o by which the sensing element increases in temperature due to the conversion of kinetic energy into heat energy. At the low flows herein considered, this source of error may be neglected in comparison with the radiation and conduction errors.

In summary, the temperature assumed by the thermocouple is characteristic of a steady state in which the rate of heat transfer from the surroundings to the junction, via radiation, is equal to the rate of heat transfer from the junction to the surroundings via convection and conduction.

Assuming that the conduction error is made negligible by proper insulation, etc., then, in steady state,

$$Q_R = Q_c \tag{5}$$

i.e., the radiated heat in equals the convected heat out. Furthermore,

$$Q_c = h_c A_p (T_p - T_g), \text{ BTU/hr} \tag{6}$$

and

$$Q_R = \sigma \epsilon_p A_p F_a (\bar{T}_w^{\,4} - T_p^{\,4}), \text{ BTU/hr} \tag{7}$$

It is more convenient to put the latter equation into a form similar to that for convective heat transfer; thus,

$$Q_R = h_r A_p (\bar{T}_w - T_p) \text{ BTU/hr} \tag{8}$$

For this case, the radiative heat transfer coefficient, h_r, can be computed, with only negligible error for most practical application, from

$$h_r = 4\,\sigma\,\epsilon\,F_a{}' \left(\frac{\overline{T}_w + \overline{T}_p}{2}\right)^3 \qquad (9)$$

The dependence of this coefficient on the cube of the average absolute temperature (instead of the 4th power) is merely a matter of convenience in calculation and may be used where a fairly constant temperature difference and a varying absolute temperature may be assumed (Ref. 3, p. 125).

Combining the above equations gives a measure of the error of the probe in terms of the temperature difference between the walls and the gas:

$$\text{Error, } T_p - T_g = \frac{h_r\,(T_w - T_g)}{h_r + h_c}$$

$$\text{\% Error, } \frac{T_p - T_g}{T_w - T_g} = 100\frac{h_r}{h_r + h_c} = \frac{100}{(1 + h_c/h_r)} \qquad (10)$$

where A_p = Probe area, ft^2

$F_a, F_a{}'$ = Geometric factors for radiation

h_c = Convective heat transfer coefficient, $BTU/hr\text{-}ft^2\ ^\circ F$

h_r = Radiative heat transfer coefficient, $BTU/hr\text{-}ft^2\ ^\circ F$

T_g = Effective gas temperature (= static temperature plus recovery factor times total minus static)

$\bar{T}_w$ = Average wall temperature for radiation °F (a complex quantity consisting of a combination of shape factors and wall temperatures)

ϵ = Total radiant emittance

σ = Stephan - Boltzmann Constant

The above development is taken from Reference 3 with minor changes to fit the present situation.

Equation (10) clearly brings out the fact that, if the convective heat transfer coefficient is extremely large compared to the radiative heat transfer coefficient, the per cent error approaches zero, i.e., probe temperature equals gas temperature. On the other hand, if the radiation is extremely high, the error approaches 100%, i.e., probe temperature equals wall temperature.

Equation (10) also shows that as long as the radiation is not zero and there is a difference between gas and wall temperature, even if no other sources of error are present, the probe temperature can never equal the gas temperature.

Turning to the results of the present test, the marked improvement in going from a 1 in. long single-shield specimen to a 2 in. long single-shield specimen (CF Figures 2A and B) is attributed to a change in "shape factor". Due to the shortness of the former shield, the thermocouple junction "sees" some of the radiating wall directly, out through the ends of the shield; the longer shield, on the latter specimen, "shades" the junction better.

Reasons that would account for the large discrepancy between the two samples of the 1 in. long single-shield specimen (Figure 4) are not readily apparent. Visual examination did disclose some differences between the two samples, but the major difference, that the junction of the better semple (specimen #1) was almost twice as large as that of the poorer sample, argues for a discrepancy the reverse of that actually observed. That is, specimen #2 (with the smaller junction) should have been the more accurate. Such an anomaly (and others) is not peculiar to the present investigation, however, as noted in Reference (3). What complicates matters further, in the case of the 2 samples above, is that the insulation was found to have worked its way out of the shield support(2) of sample #1 (it is not known at which point of the investigation this occurred), and the fact that its stem (i.e., shield support) is 1.14 in. long as compared to sample #2 the stem of which is 1.01 in. long.

The fact that the 2 in. long double-shield specimen (Figure 4C) is not a material improvement over the 2 in. long single shield specimen (*Cf* Figures 2B and C) may well be due to the fact that the inner shield is not completely shaded from radiation. Geometric considerations, which demonstrate that a strip at each end of the inner shield sees the radiating wall directly, lend credence to this view.

As regards the two sample umbrella-shield specimens (Spec's 8 and 9; *Cf* Figure 4A), the only conspicuous difference between them is that the worse sample (Spec.#9) has a more sharply curved shield which, possibly, focused the radiation in the vicinity of the junction. Measurement disclosed that the stem (shield support) of the poorer sample (Spec. #9) is 1.50 in. long while that of the better sample (Spec. #8) is 1.58 in. long.

It was in an effort to exclude the possibility of focusing, as well as to inhibit the change in air flow pattern accompanying a change in specimen orientation,

Note (2): This seems to be a common complaint against the use of Sauereisen #7 paste. The other specimens contained a ceramic insulator in the stem bonded ~~with Narmco~~ metal bond #2021.

that the flat umbrella-shield specimen (Figure 4E) was evolved.

At worst, a half-shield would seem to afford half as much protection against radiation. This is not so much due to the fact that the point of attachment, being heated by the radiant source, will be at a higher than air temperature (and thus radiate directly to the unprotected "bottom" of the instrument) as it is due to the fact that the "bottom" of the instrument will be unprotected from reflected radiation. The amount of radiation reflected from surfaces near the thermocouple is not so much dependent on the temperature of the surfaces as it is on their reflectivities or emissivities.

The relatively poor performance (Figure 2G) of the Revere instrument (Photo p. 74) was anticipated from its construction. Previous work (Reference 2) indicates that when the inter-shield spacing is reduced below a certain minimum value the several shields act as a unit, i.e., offer no more protection than a single shield. This would seem to follow from the fact that heat conduction along the intershield supporting struts will be greater the shorter they are (also the thicker they are, and the more numerous - factors that seem to have been overlooked in the construction of the present instrument).

Furthermore, since both the viscosity and conductivity of air increase with temperature, some contribution to the increase in ~~error~~ with smaller spacing is probably made by the retarded convective heating in the annular passages and by heat conduction between the shields.

The Northrop triple-shield specimen (Figure 4D), though the shields were not polished (The Revere instrument had highly polished shields), performed considerably better (as shown by the data of Figure 2D.)

Since an investigation such as the present one could be continued almost indefinitely, assessing the effects of varying factor after factor, it was felt that a more profitable line of attack would consist in an outright attempt to design a good instrument based on theory tempered with the facts discovered above. Thus, an instrument was evolved which differs in several essential respects from any heretofore considered: shield material, size and geometry, and method of inter-shield support.

Of the four new specimens constructed (Figures 4E F & G and Photos pp.71,73) the best results were achieved with a 3 in. long outer, 2 in. long inner aluminum shield specimen (Figure 4G), the inner shield being attached to the outer with two slender threaded screws. This double-shield instrument performed considerably better than either of the triple-shield specimens considered, as illustrated by Figures 2H, G, and D.

Aside from the fact that aluminum cannot be silver soldered nor welded readily, the use of screws as a shield support has the added advantage that the threads act as minute fins and reduce the amount of heat conducted from the outer to the inner shield. Limiting the supports to two screws further reduces the area available for heat transfer by conduction from outer to inner shield and should give sufficient rigidity for the use contemplated. The use of aluminum, instead of the usual stainless steel shields, is dictated by the fact that aluminum, even when oxidized, has an emissivity only about 25 per cent that of stainless steel. The nearly universal acceptance of stainless steel shields may be traced to the precedent established in a long line of high gas temperature studies (such as obtained in slag-bearing gases in pulverized-coal-fired, or oil fired furnaces) and is uncalled for in applications such as the present one where the air temperatures are not expected to go much beyond 200°F. Extending the outer shield beyond the inner will have the effect, noted previously, of keeping more of the inner shield "in the shade". A 1 in. long inner, 2 in. long outer shield specimen might perform as well (this would have to be ascertained experimentally), but it was not tried due to the marked improvement noted above in going from a 1 in. long single-shield to a 2 in. long single specimen.

As mentioned previously, strictly speaking, the results of the present test apply only in the present test rig. However, there is little reason to believe that the best instrument in the present experimental set-up will not also be the best instrument outside of it; though this instrument may not perform as well in a given installation, the performance of the other specimens, it is anticipated, will be still worse. At any rate, it is desirable to use the best instrument in the light of what is known and assume it will still be best in an unknown situation when evidence to the contrary is lacking.

Objections to the use of the umbrella-shield specimens have already been dealt with above. Their greater

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over-all inaccuracy is depicted in Figure 2J.

It was felt that constricting the inner shield near the thermocouple junction (Figure 4F) would have the desirable effect of promoting the convective heat transfer from the junction as a result of increased air velocity. Such an instrument (Figure 4F) was constructed to assess the amount of improvement, if any. Unfortunately this modification resulted in a less accurate instrument (Figure 2I). Three of the 5 strands on each thermocouple wire had been removed, the remaining 2 strands of each wire being formed into a junction, which should have resulted in a more accurate instrument, so that, evidently, constricting the inner shield has a more deleterious effect than brought out by the present data.

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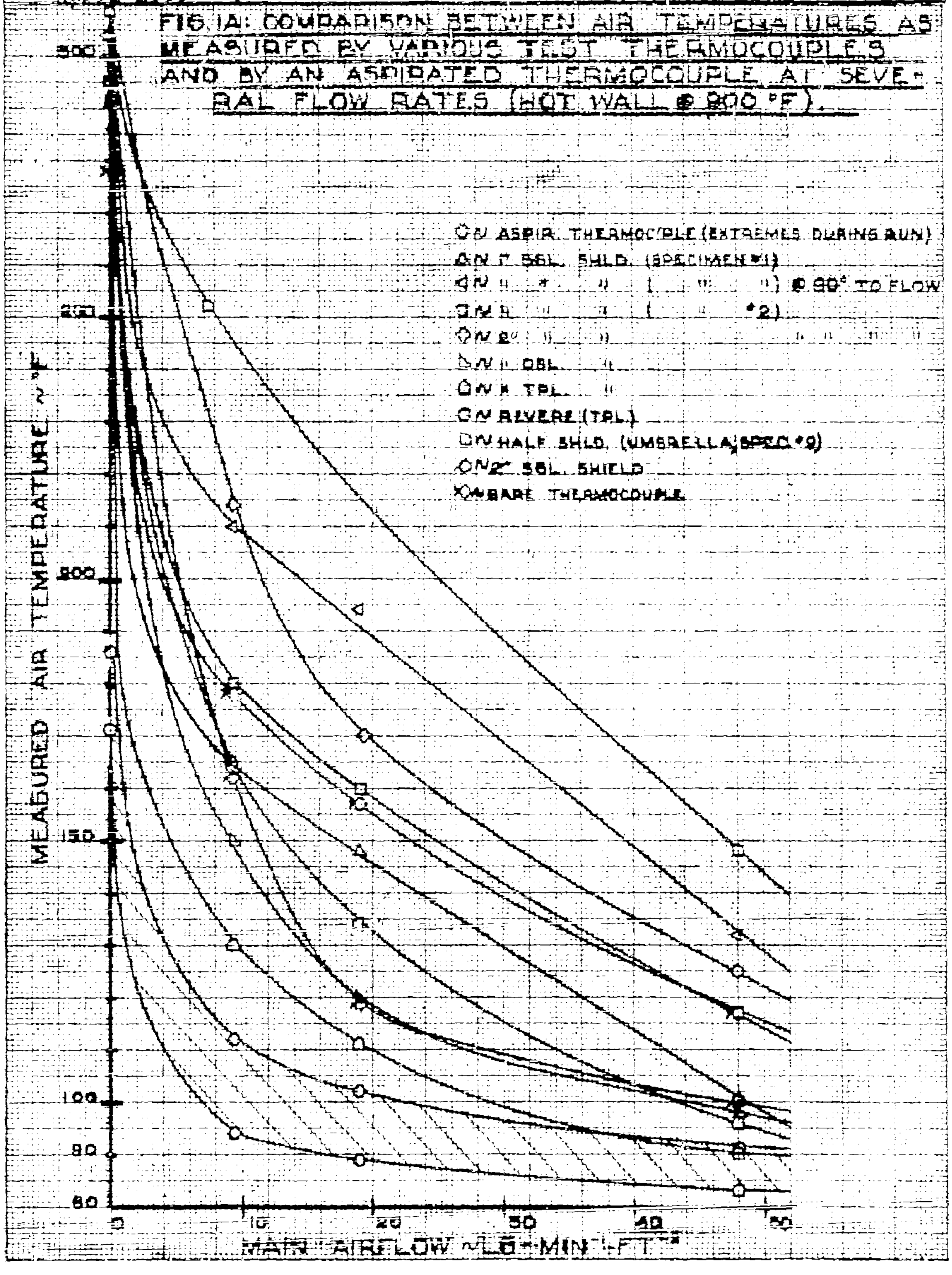

FIG. 1A: COMPARISON BETWEEN AIR TEMPERATURES AS MEASURED BY VARIOUS TEST THERMOCOUPLES AND BY AN ASPIRATED THERMOCOUPLE AT SEVERAL FLOW RATES (HOT WALL @ 800 °F).

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FIG. 18: COMPARISON BETWEEN AIR TEMPERATURES AS MEASURED BY VARIOUS TEST THERMOCOUPLES AND BY AN ASPIRATED THERMOCOUPLE AT SEVERAL FLOW RATES (HOT WALL @ 700°F)

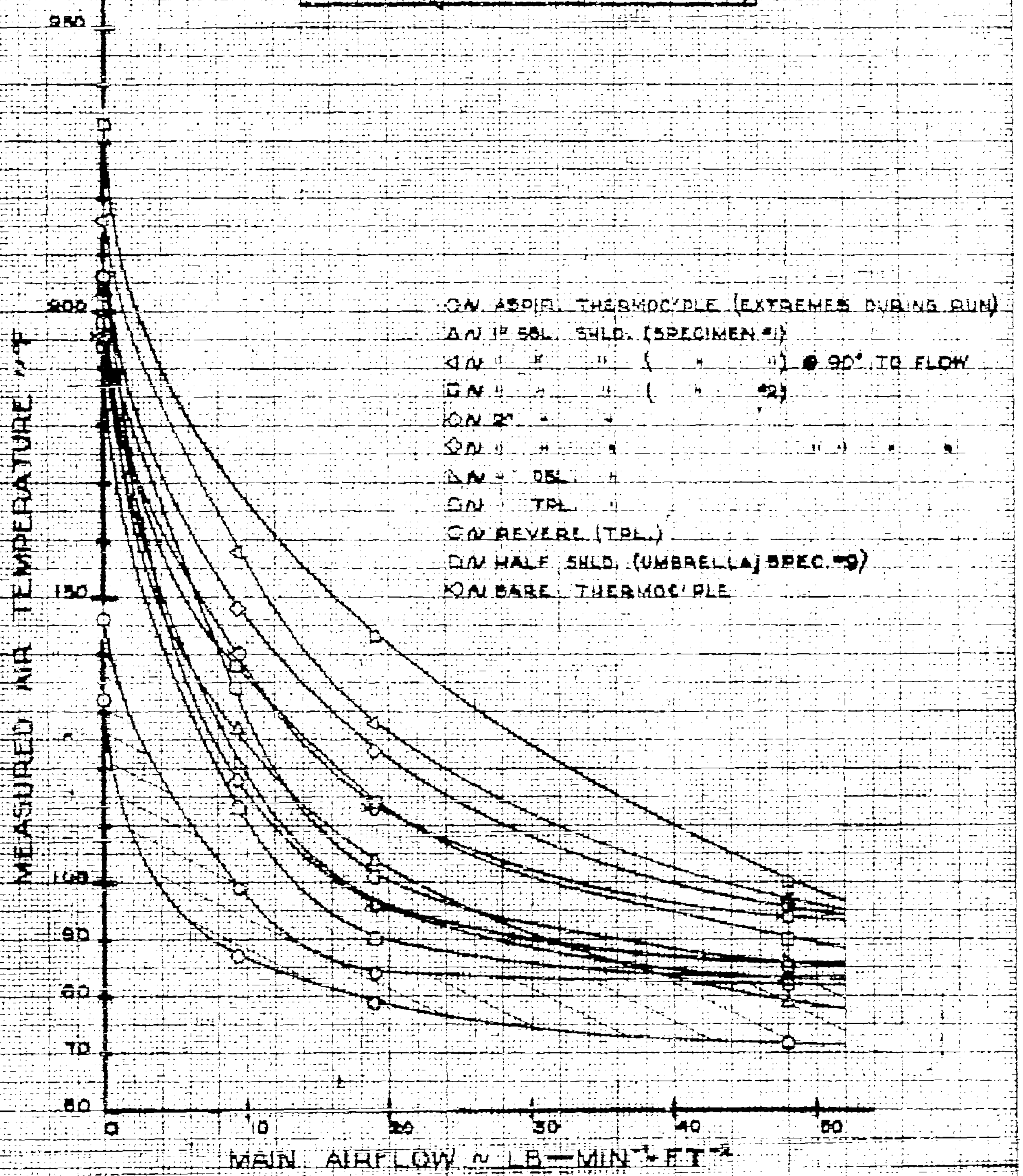

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FIG. 10: COMPARISON BETWEEN AIR TEMPERATURES AS MEASURED BY VARIOUS TEST THERMOCOUPLES AND BY AN ASPIRATED THERMOCOUPLE AT SEVERAL FLOW RATES (HOT WALL @500°F)

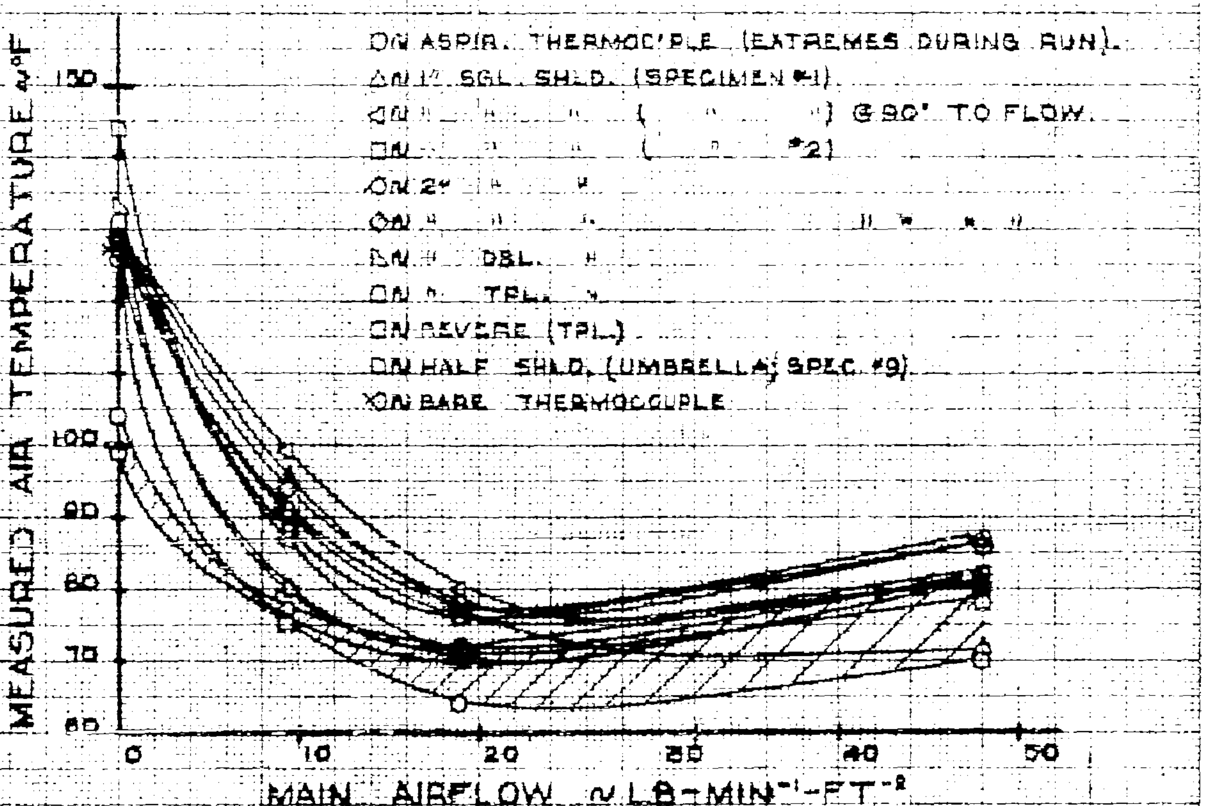

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FIG. 2A: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 1" LONG SIDE SHLD TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

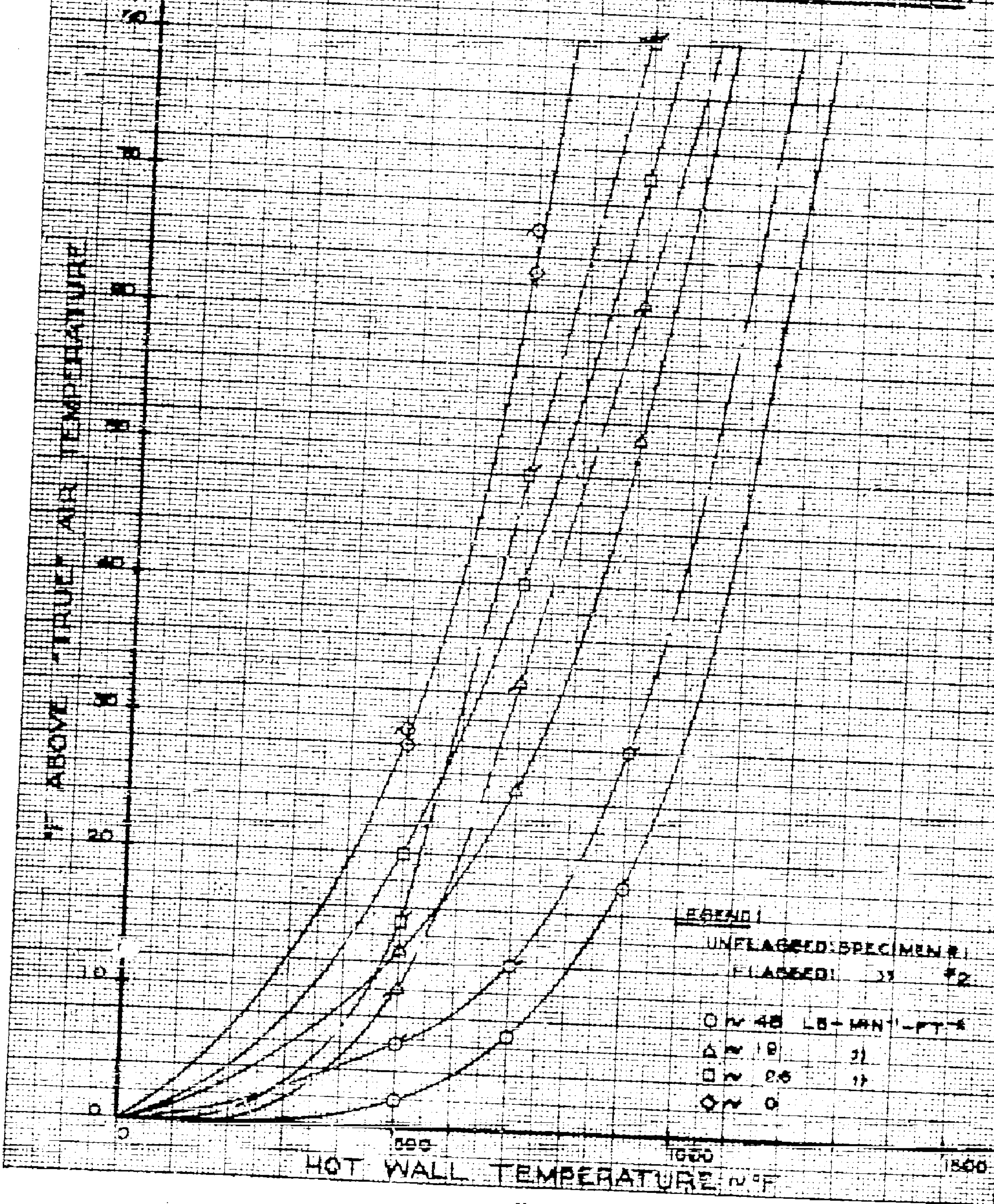

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FIG. 28: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 2" LONG SSL. SHLD. TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

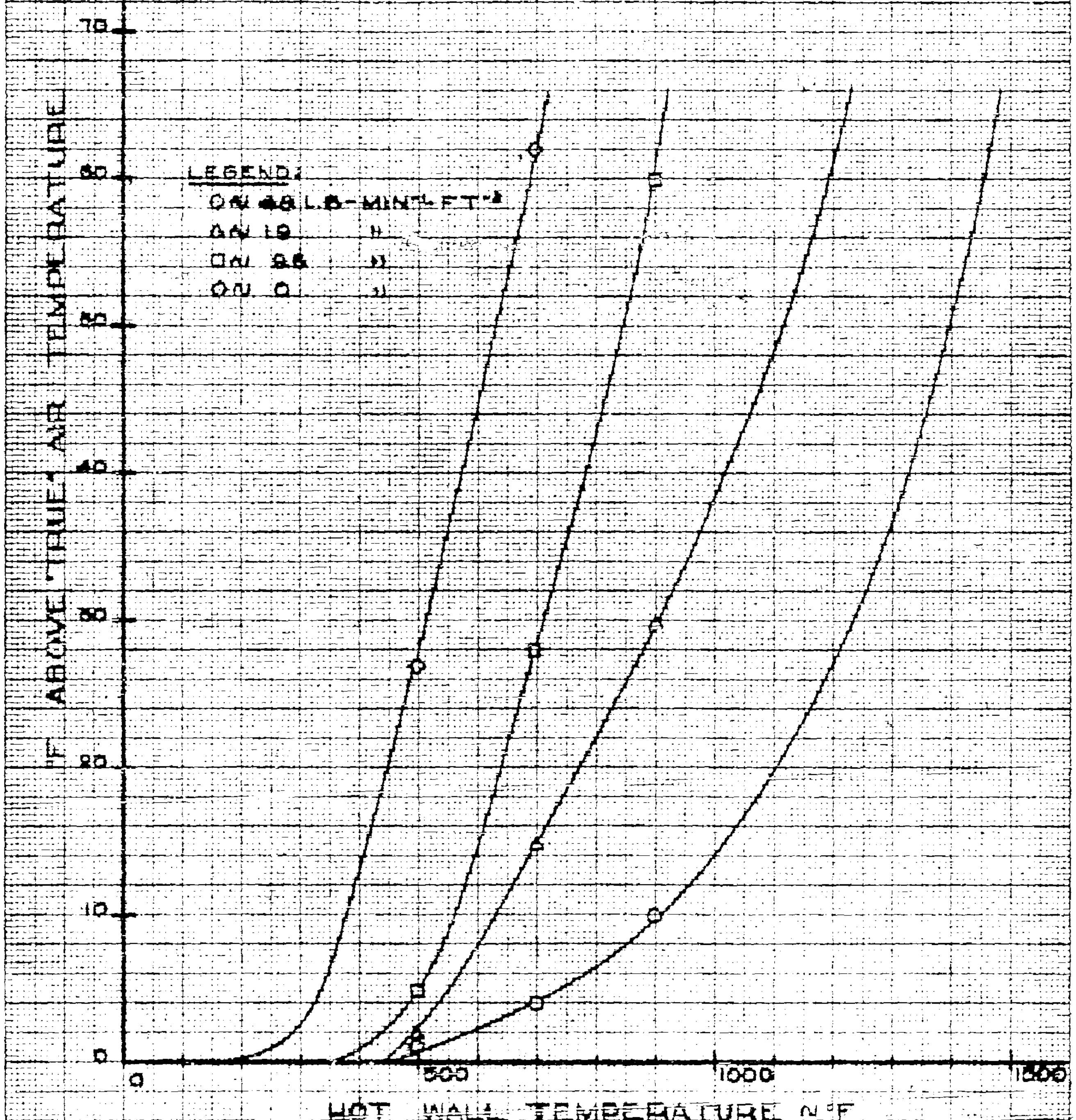

FIG.2C: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 2" LONG DBL. SHLD. TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES

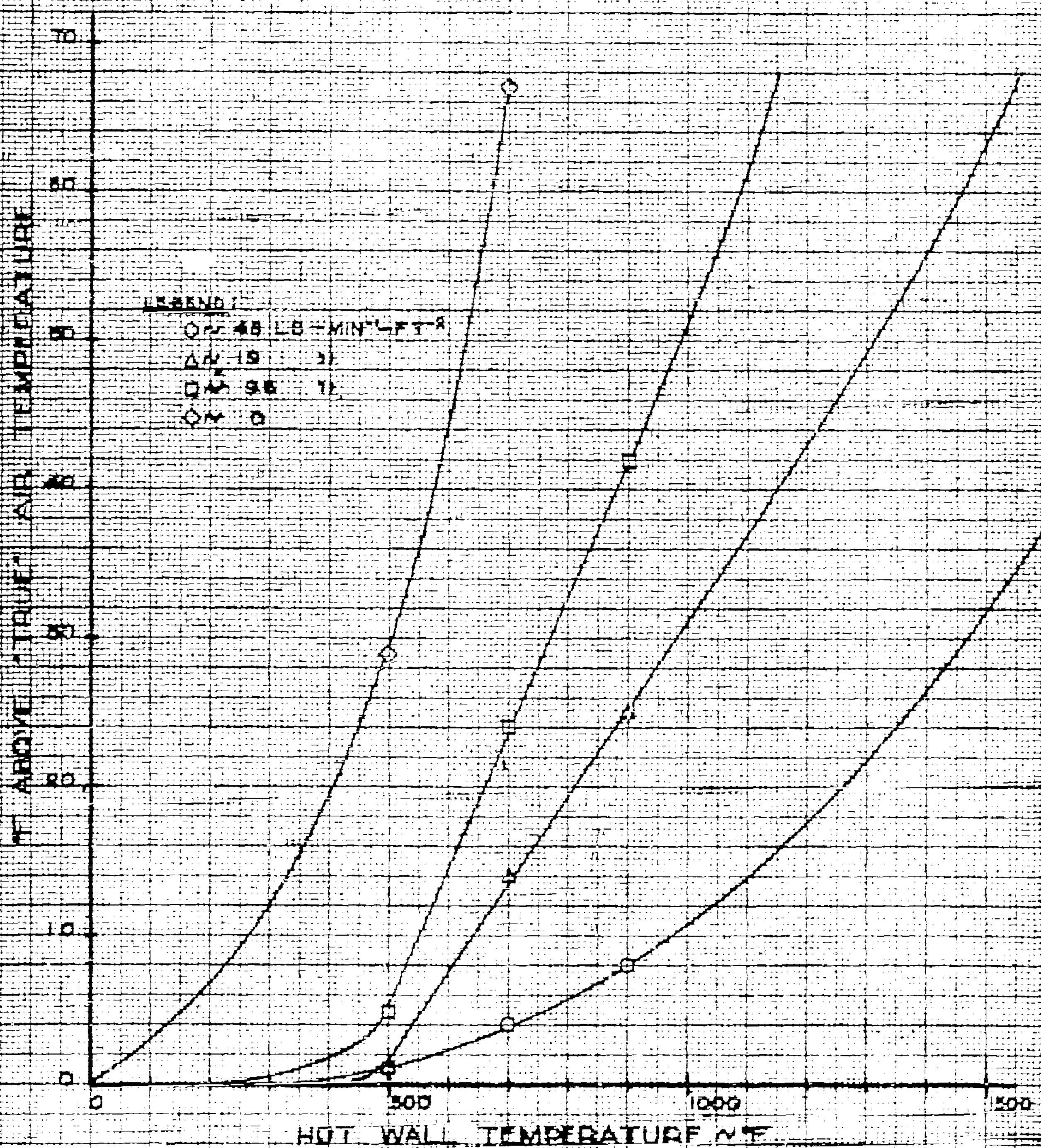

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FIG. 2D: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 2" LONG TPL. SHLD. TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

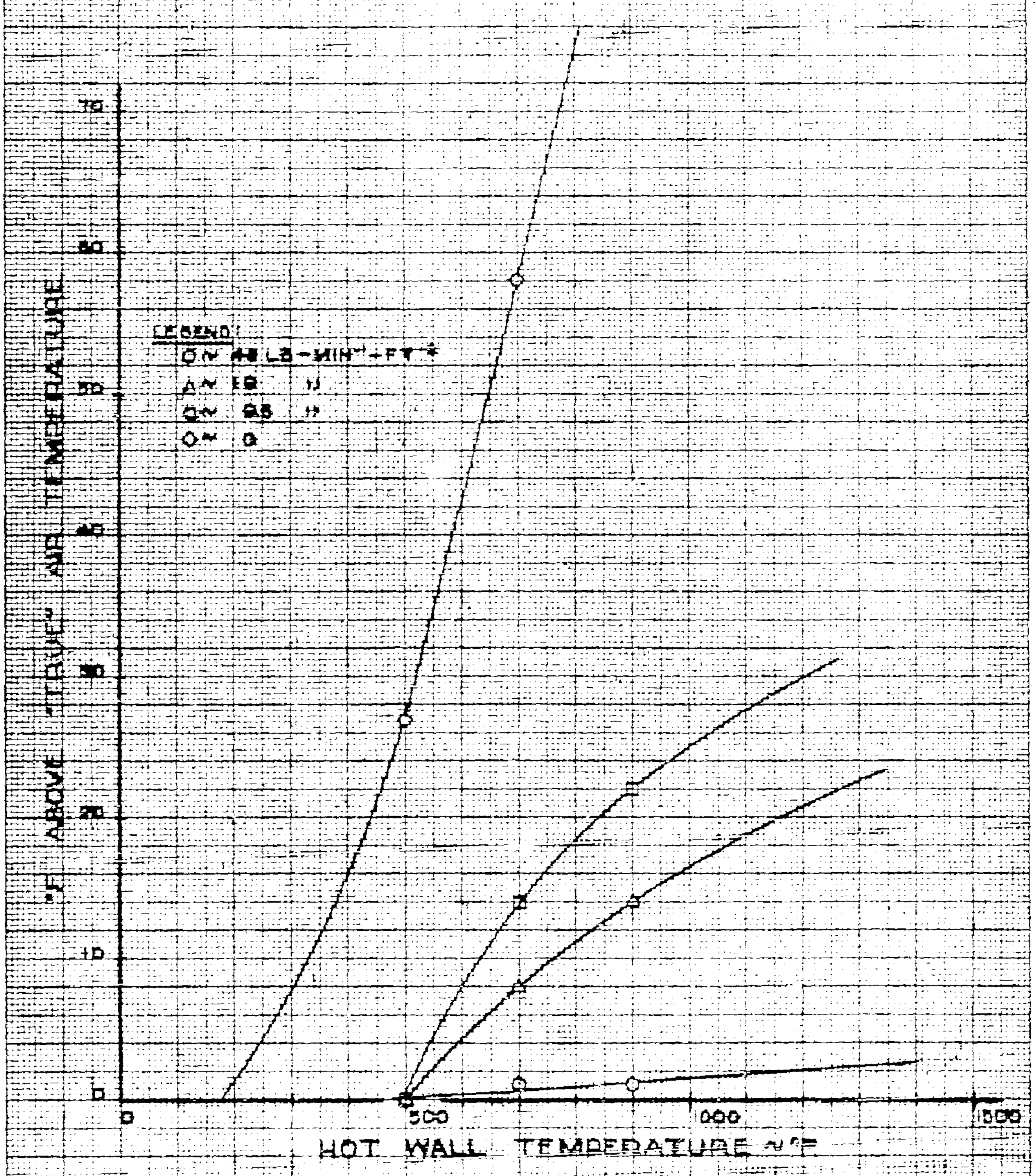

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FIGURE [illegible] °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY BARE TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

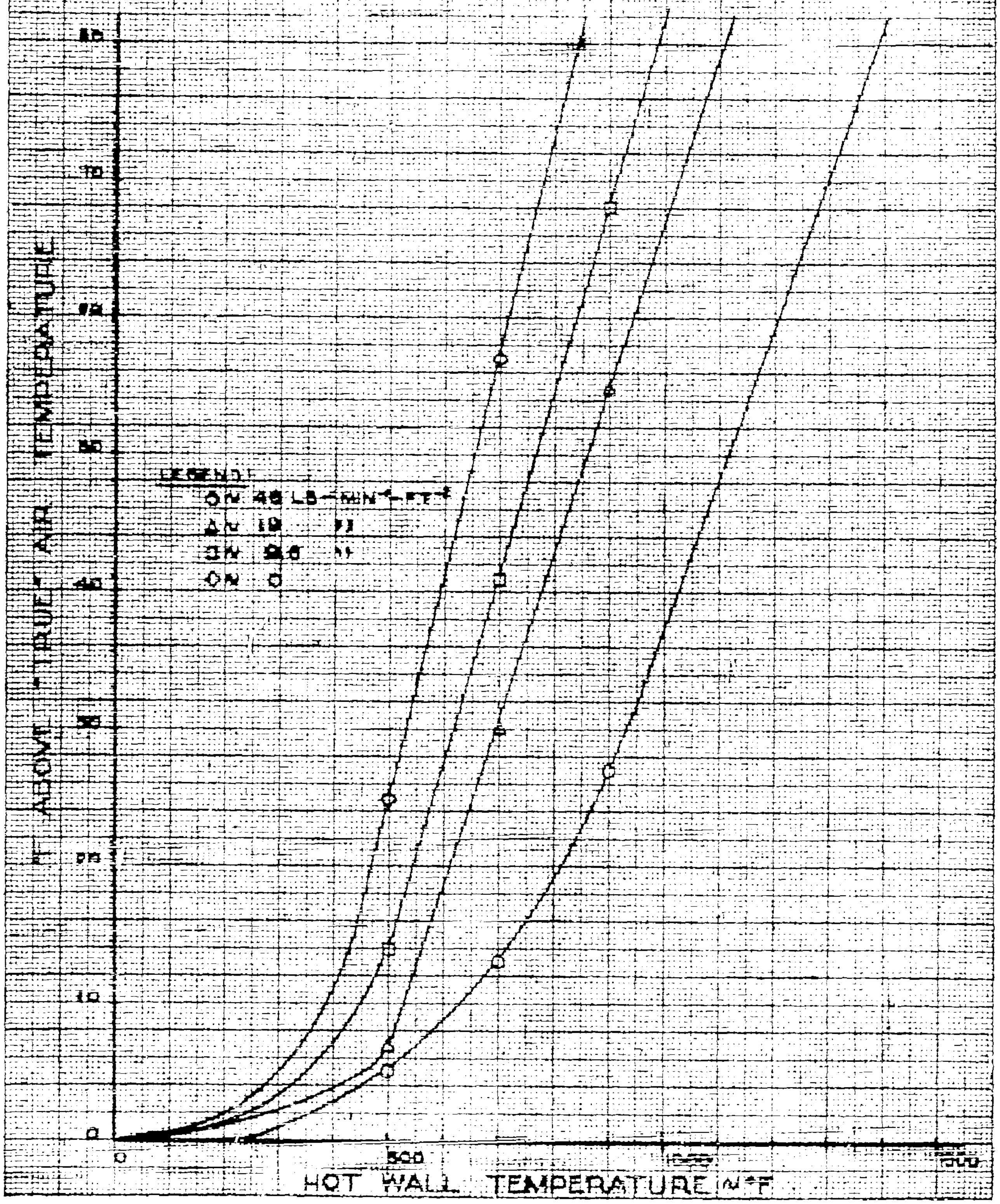

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FIG.2F: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY HALF-SHLD. TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

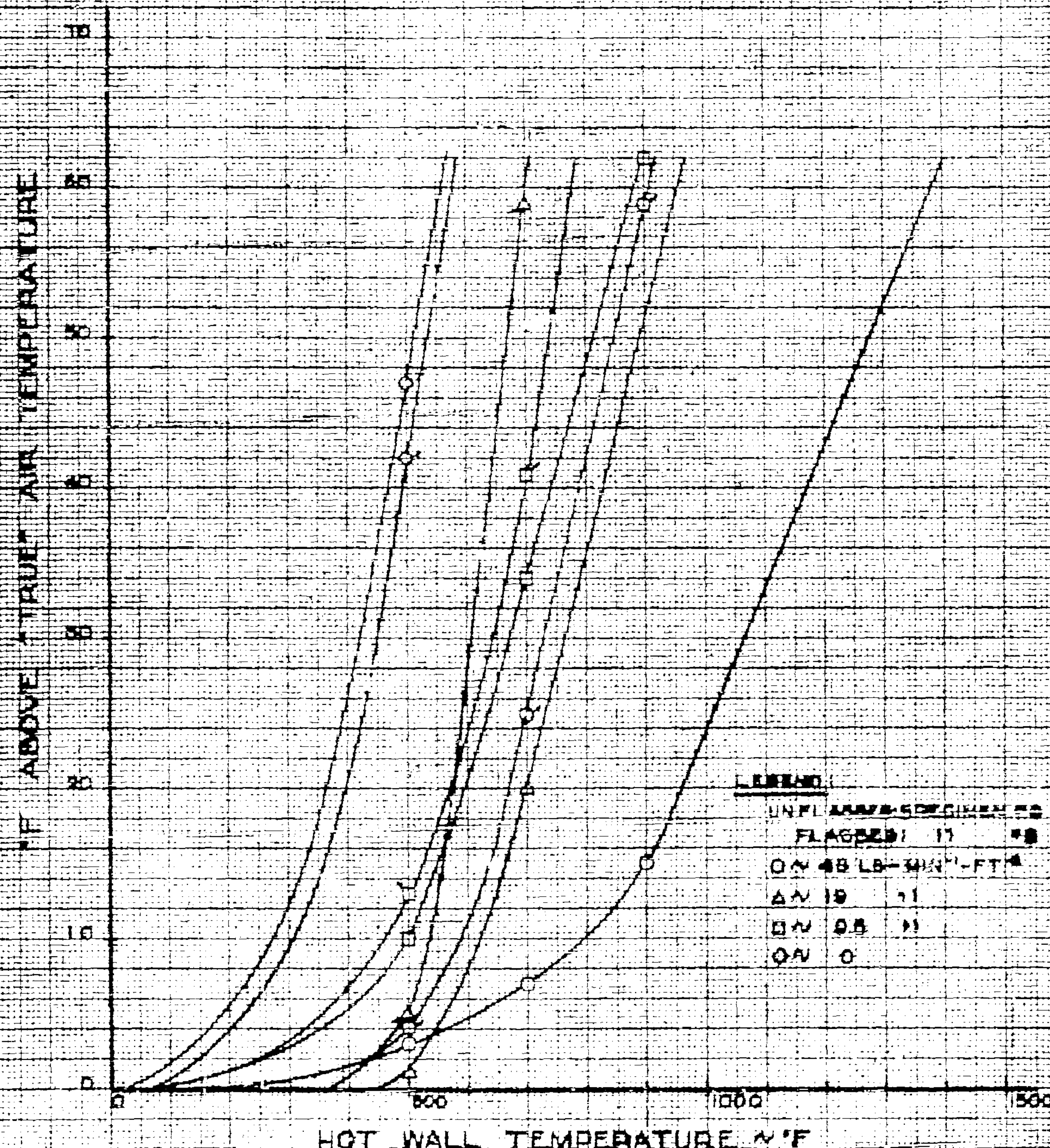

FIG. 20: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY REVERE (TPL. SHLD.) TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

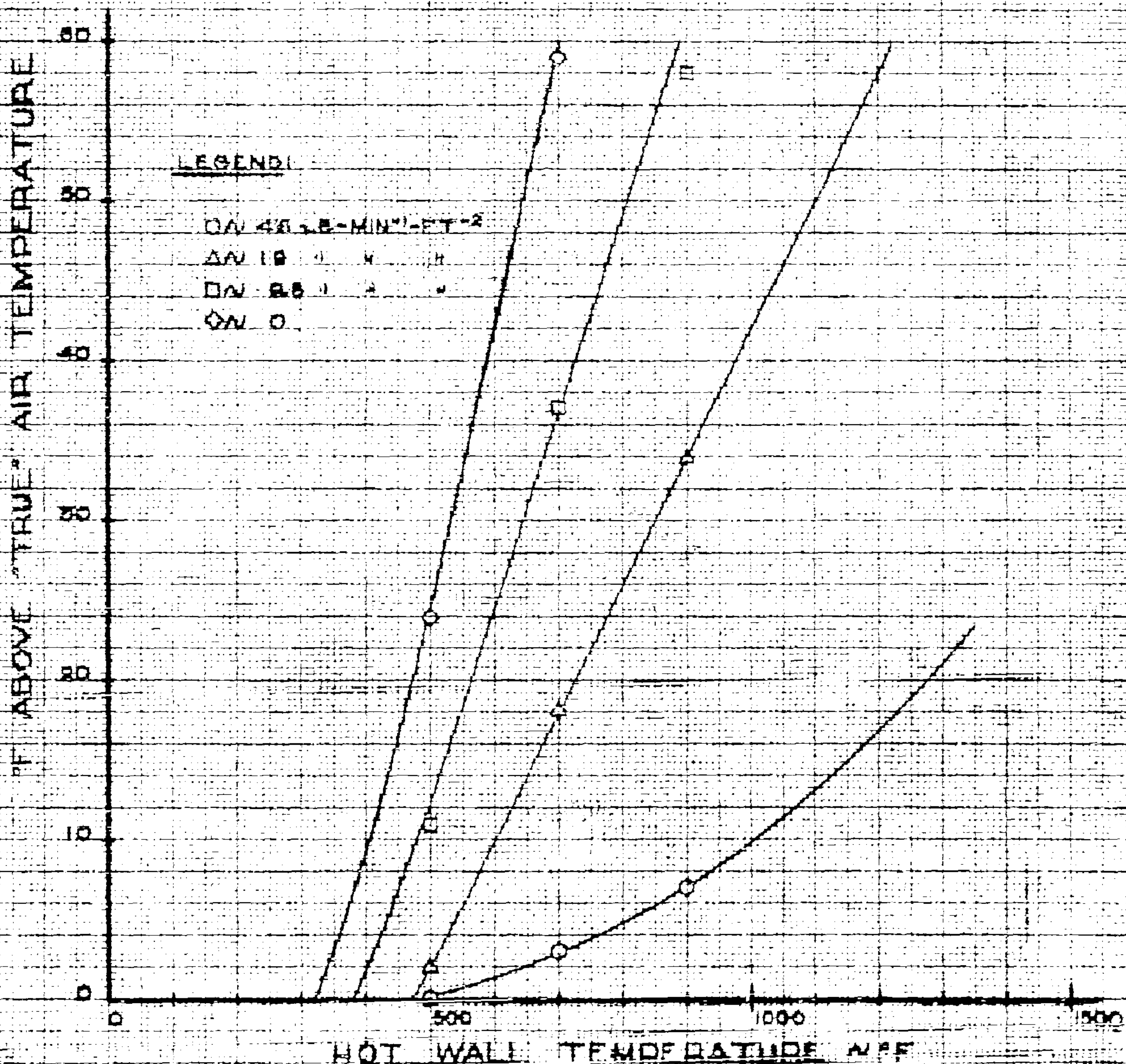

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FIG 24. °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 3" OUTER - 2" INNER ALUMINUM DBL SHLD TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

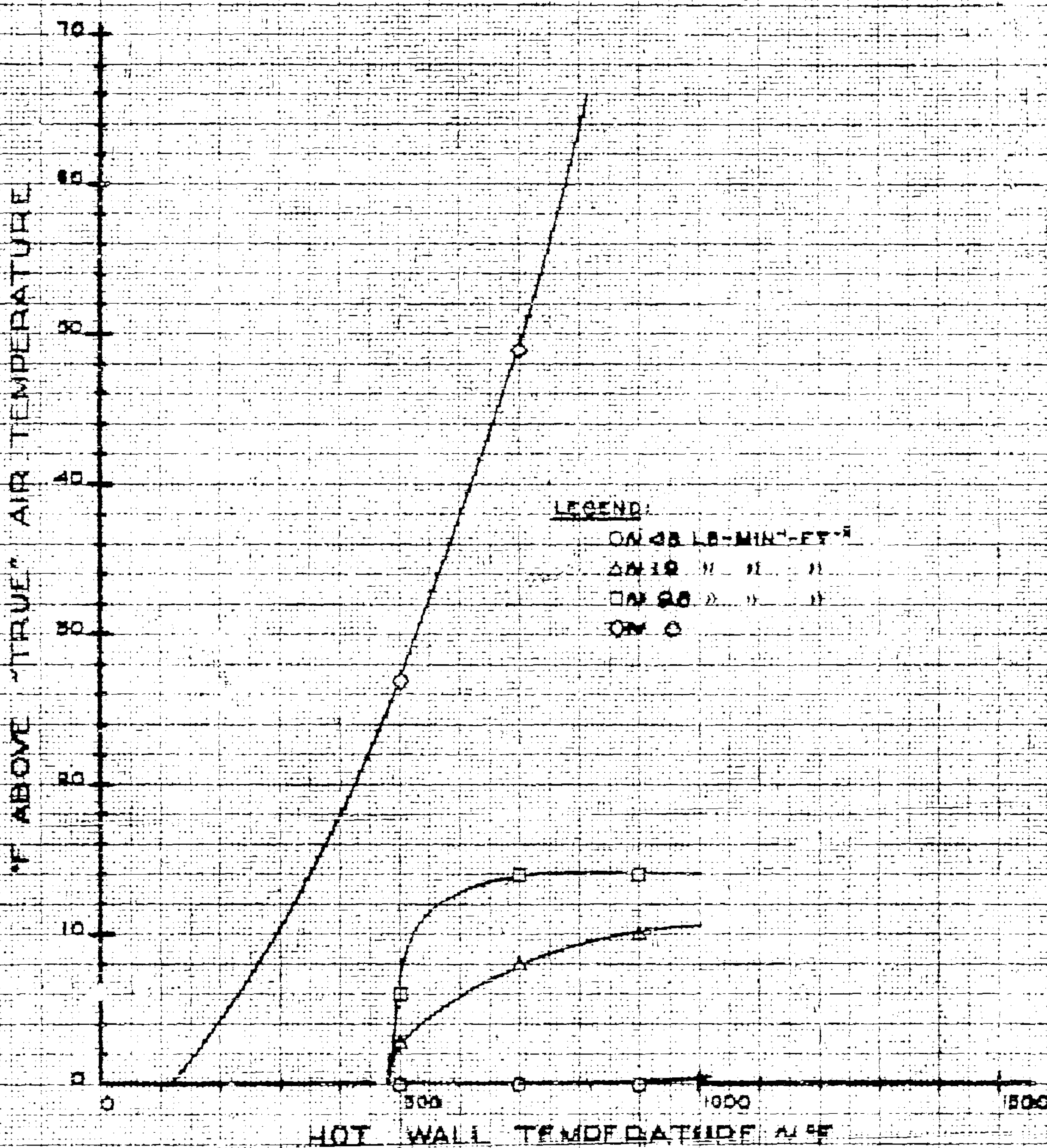

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FIG.21 °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 3" OUTER - 2" VENTURI INNER ALUMINUM DBL. SHLD. TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

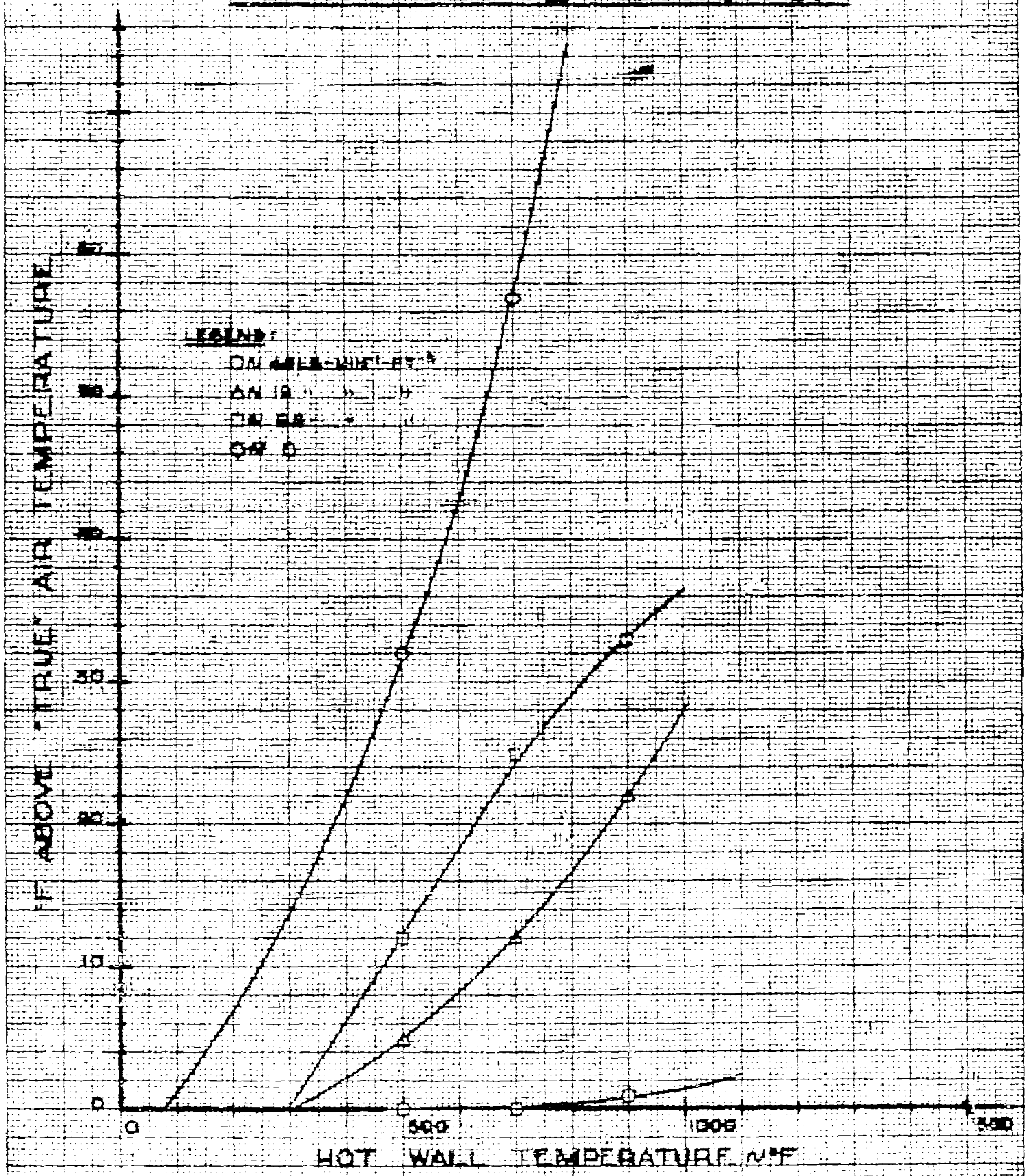

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FIG. 2U: °F ABOVE "TRUE" AIR TEMPERATURE INDICATED BY 2"×2" UMBRELLA ALUMINUM TEST THERMOCOUPLE FOR SEVERAL FLOWS AND HOT WALL TEMPERATURES.

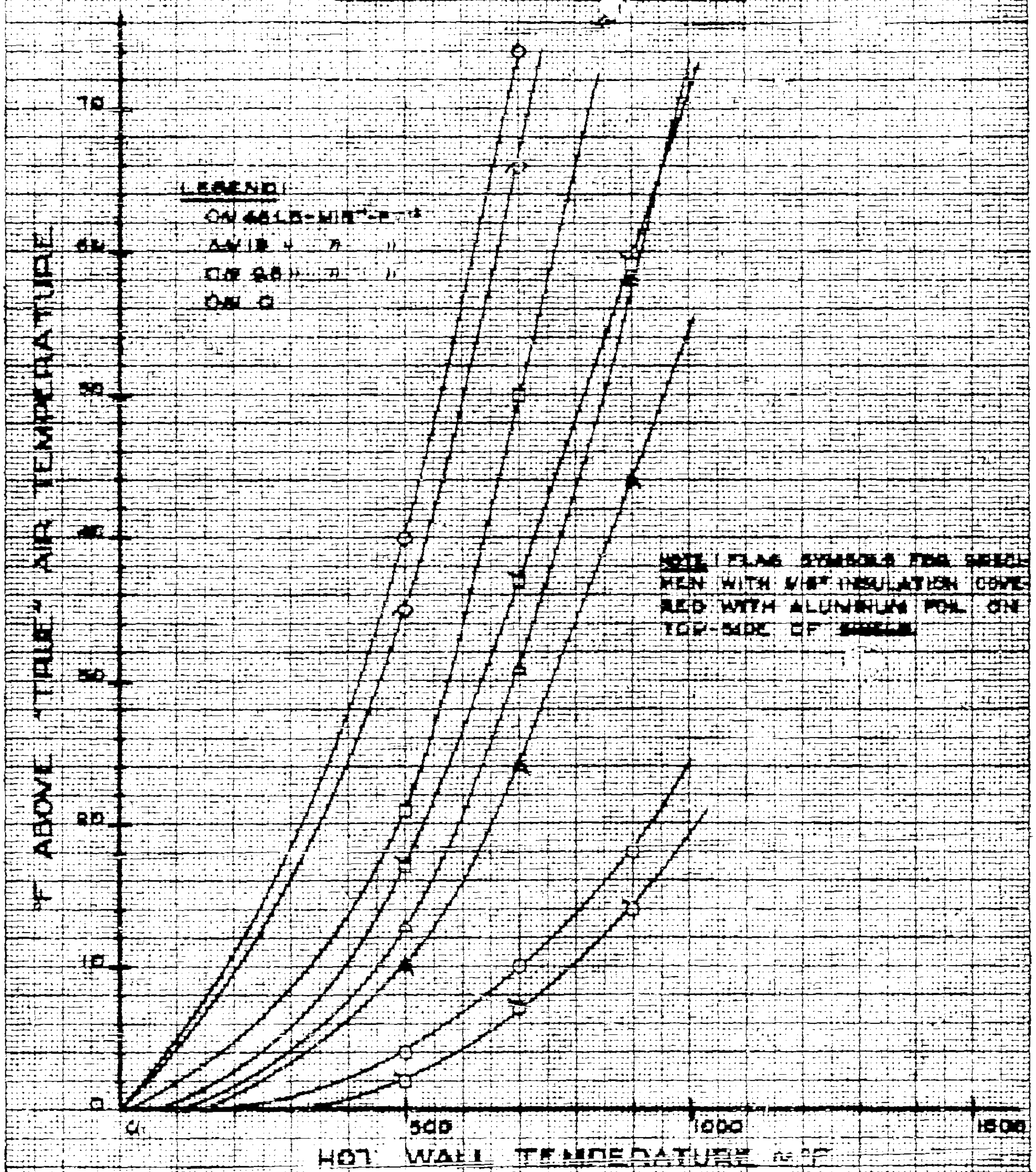

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FIG. [illegible] EFFECT OF ORIENTATION TO 46 LB-MIN⁻¹-FT⁻² FLOW ON TEST THERMOCOUPLE READING.
(1" 56L SHLD. - SPECIMEN #1)

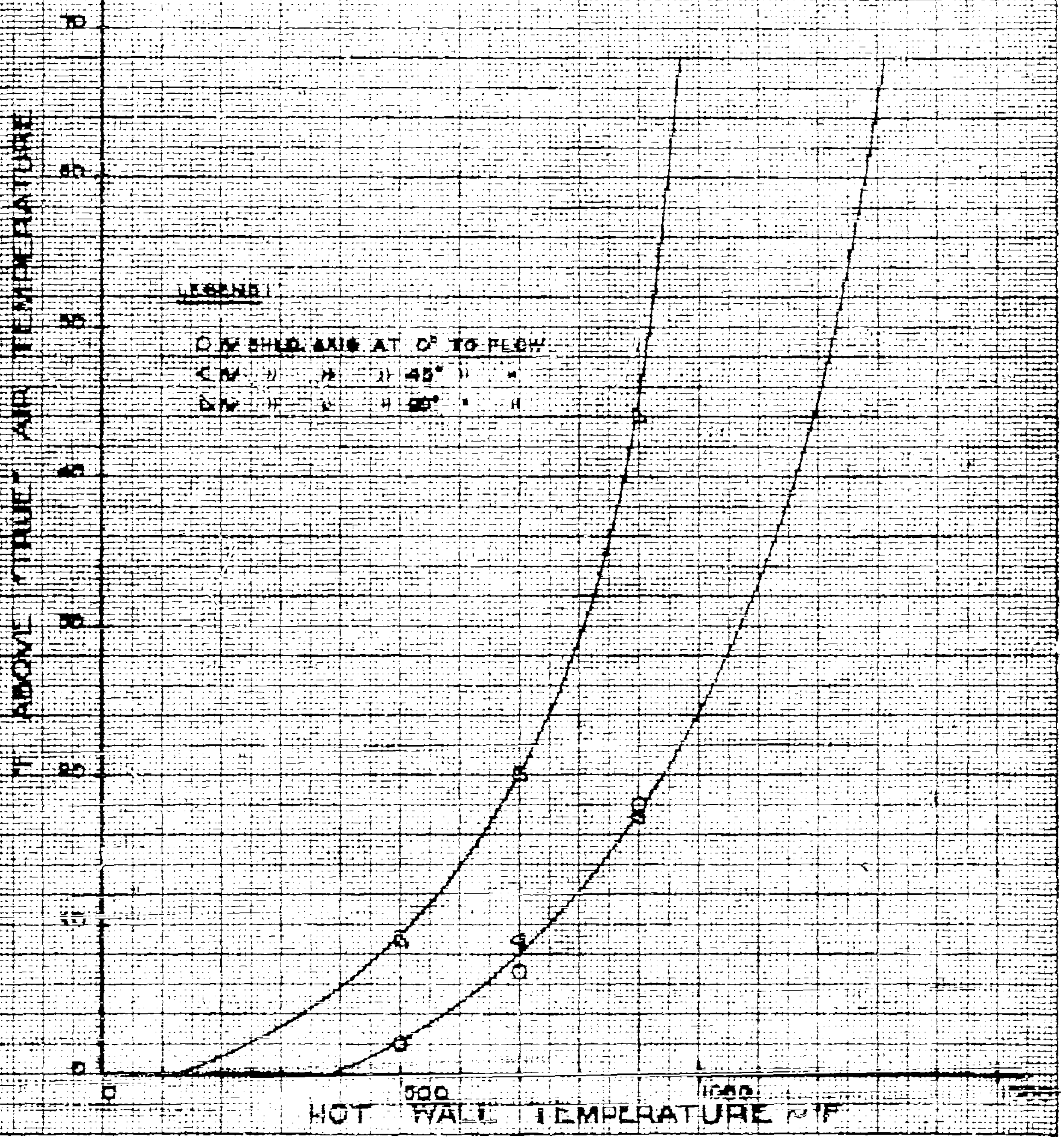

FIG. 38: EFFECT OF ORIENTATION TO 19 $LB-MIN^{-1}-FT^{-2}$ FLOW ON TEST THERMOCOUPLE READING.
(1" SGL. SHLD. - SPECIMEN #1)

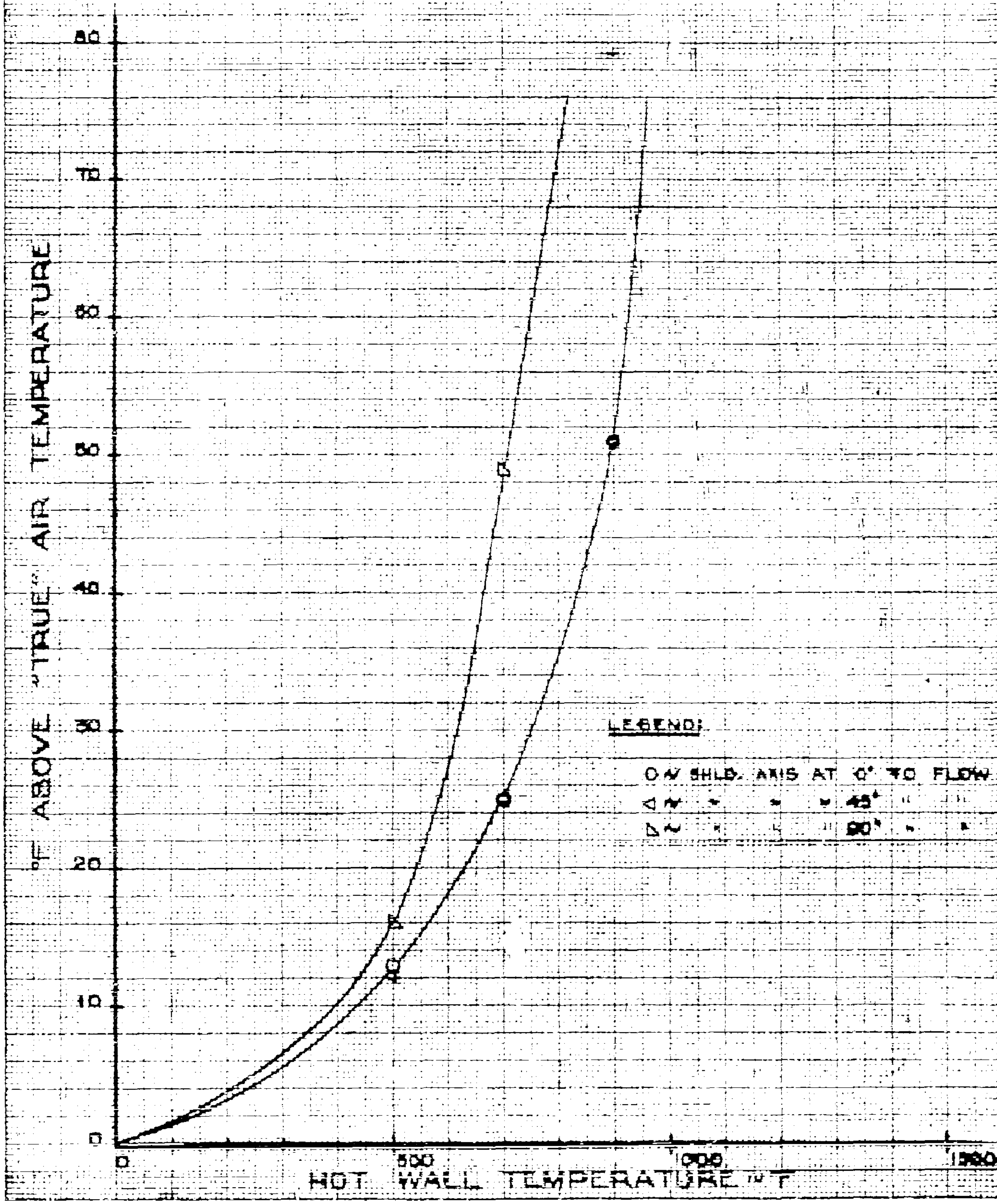

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FIG. 60: EFFECT OF ORIENTATION TO 0.5 LB-MIN FLOW ON TEST THERMOCOUPLE READING (1" SGL. SHLD SPECIMEN #1)

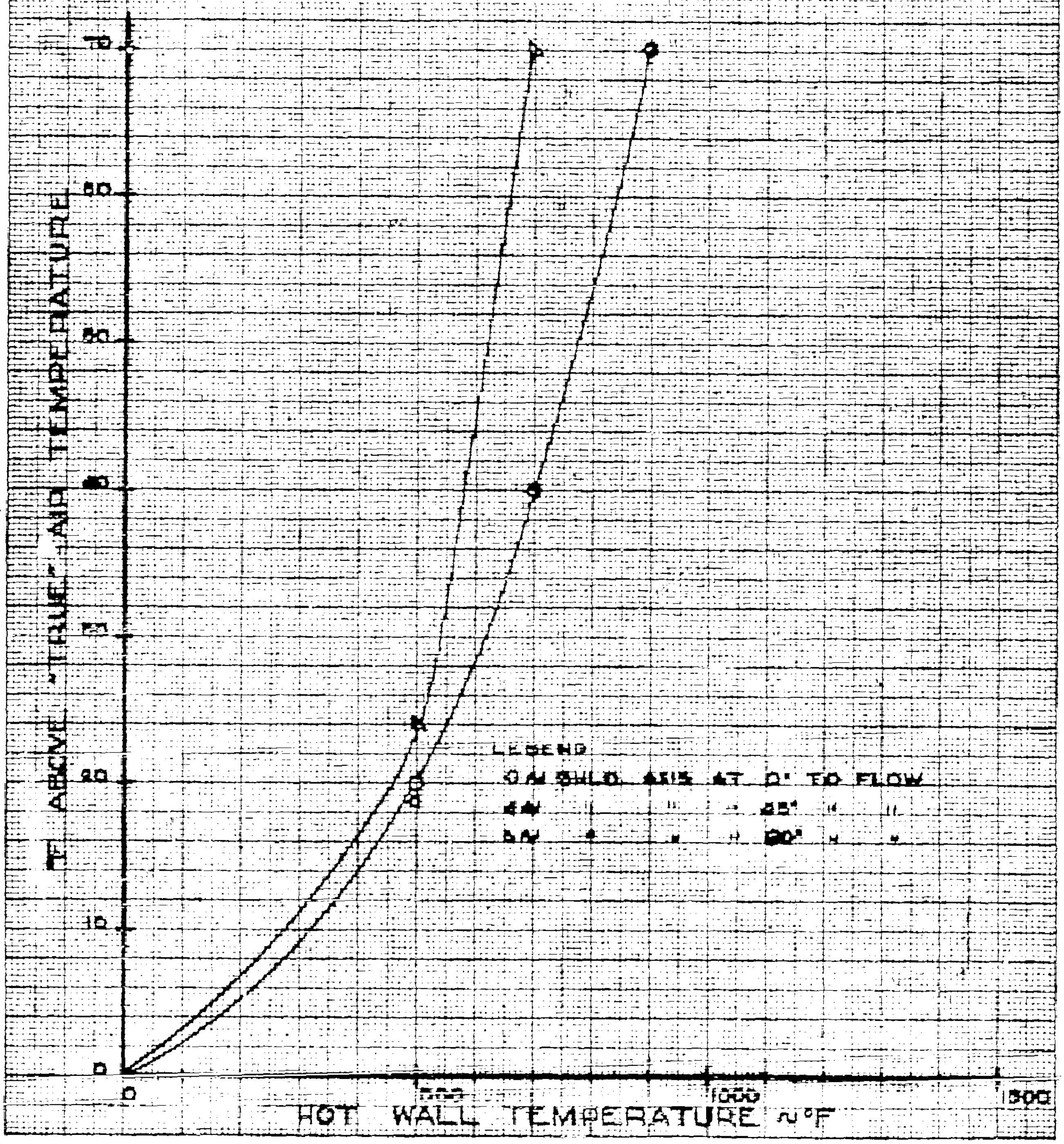

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FIG. 30: EFFECT OF ORIENTION ON TEST THERMO-COUPLE READING AT ZERO FLOW. (1" SGL. SHLD.-SPECIMEN#1)

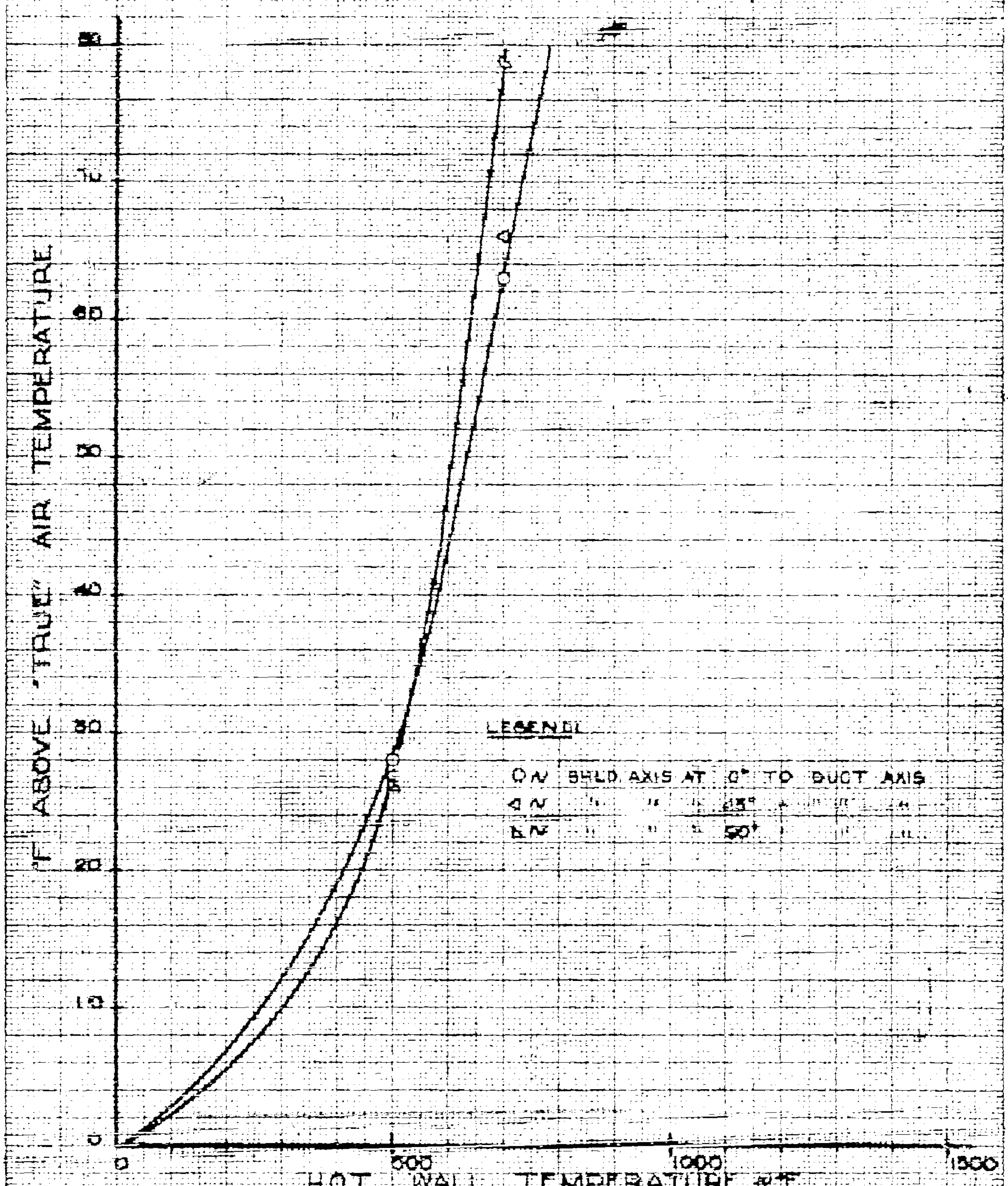

FIG.5E: EFFECT OF ORIENTATION TO 48 LB-MIN^{-1}-FT^{-2} FLOW ON TEST THERMOCOUPLE READING (2" SGL. SHLD.)

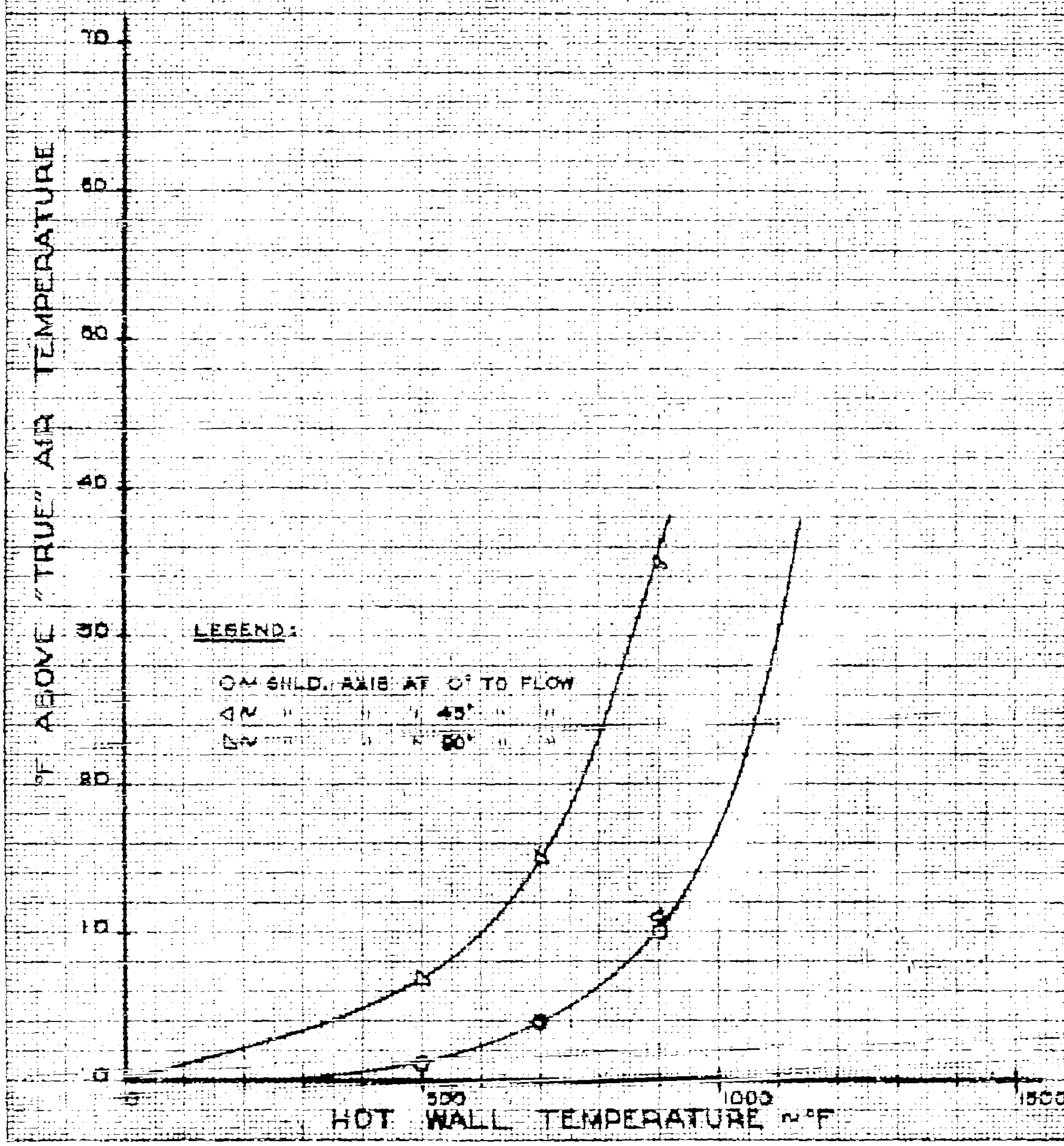

FIG. 8F | EFFECT OF ORIENTATION TO ISLE-MIN-LET FLOW ON TEST THERMOCOUPLE READING (2" SGL. SHLD.)

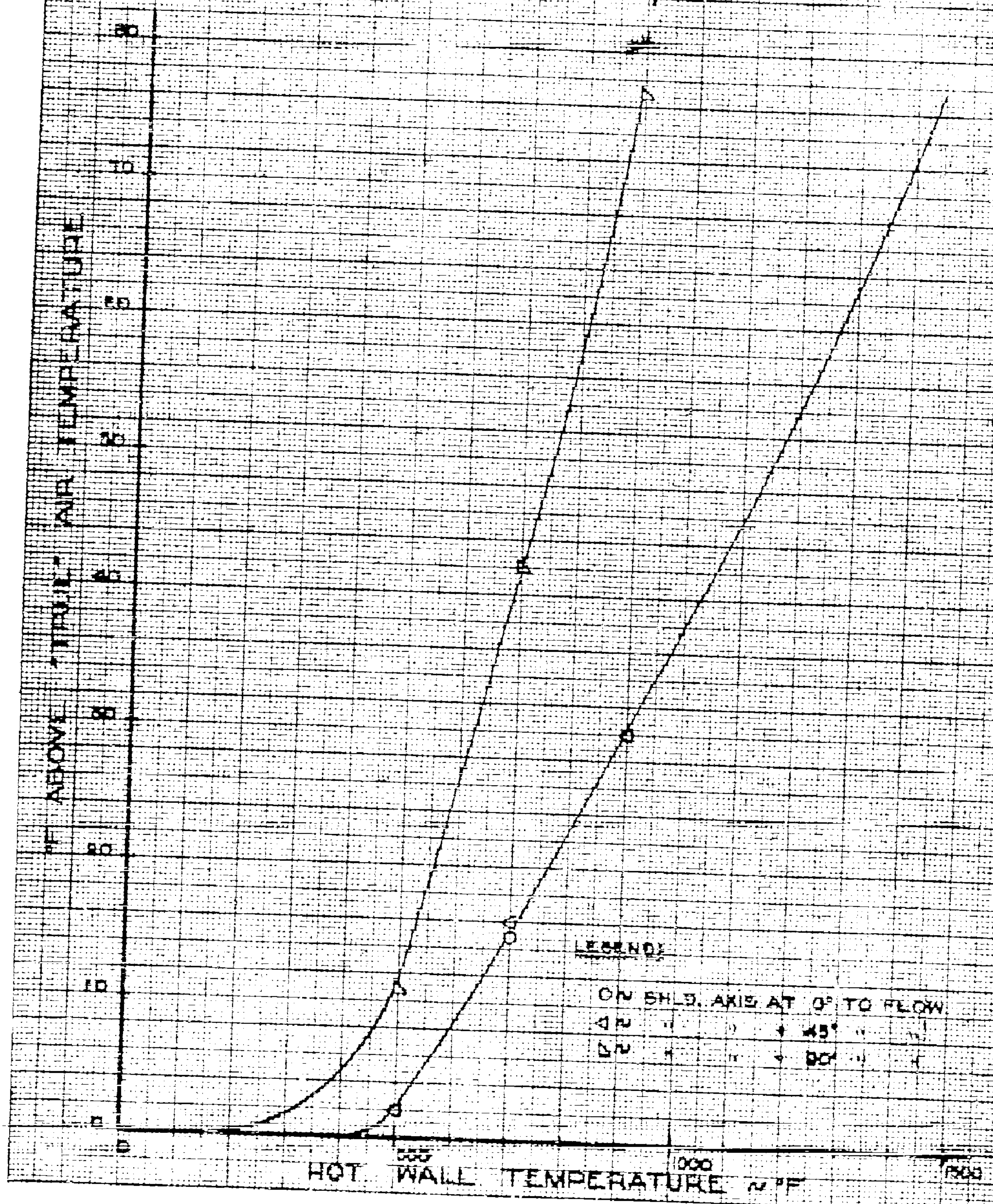

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FIG. 56: EFFECT OF ORIENTATION TO 9.6 LB-MIN⁻¹-FT⁻² FLOW ON TEST THERMOCOUPLE READING (2" SGL. SHLD.)

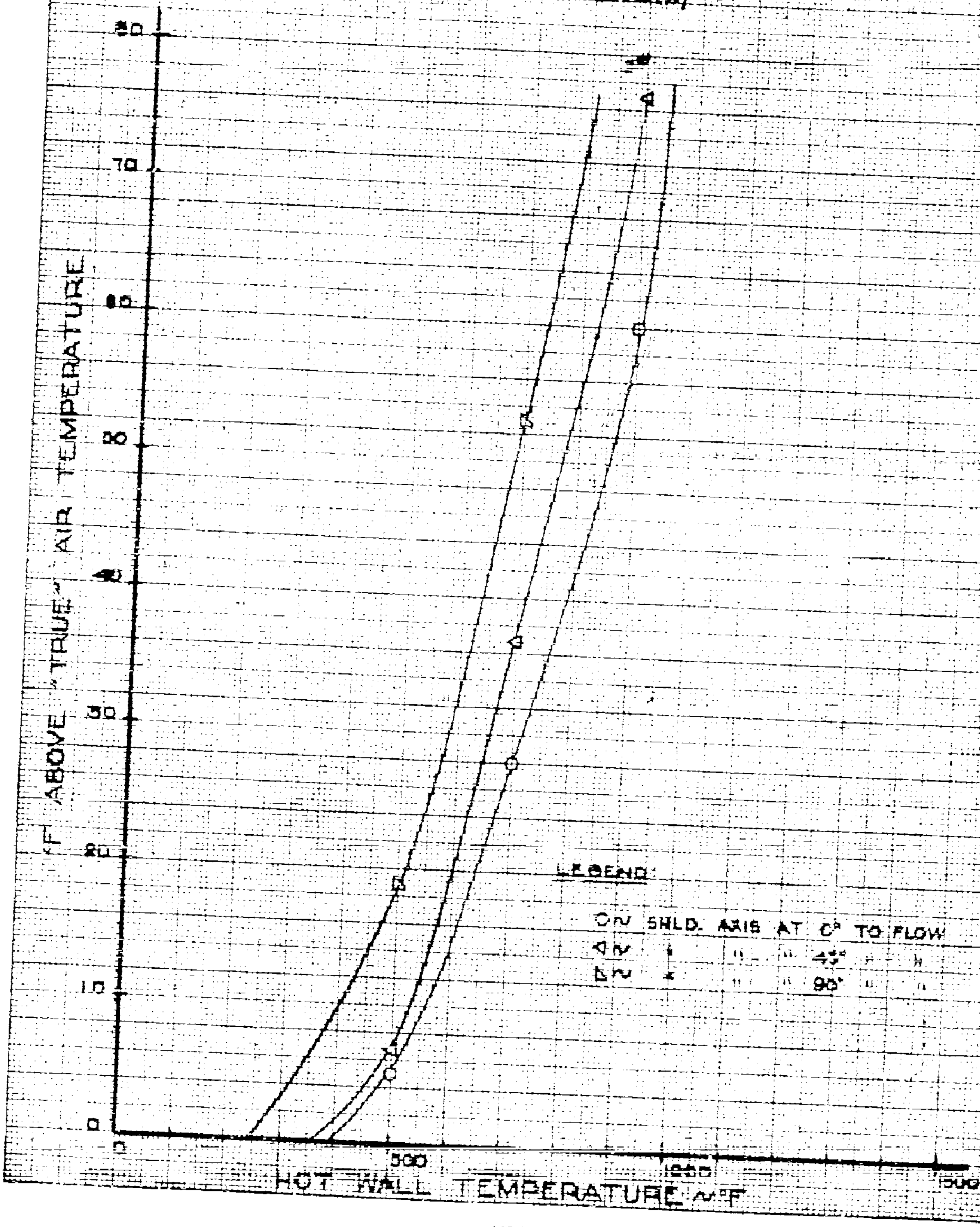

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FIG.3H: EFFECT OF ORIENTATION ON TEST THERMOCOUPLE READING AT ZERO FLOW. (2" SSL. SHLD.)

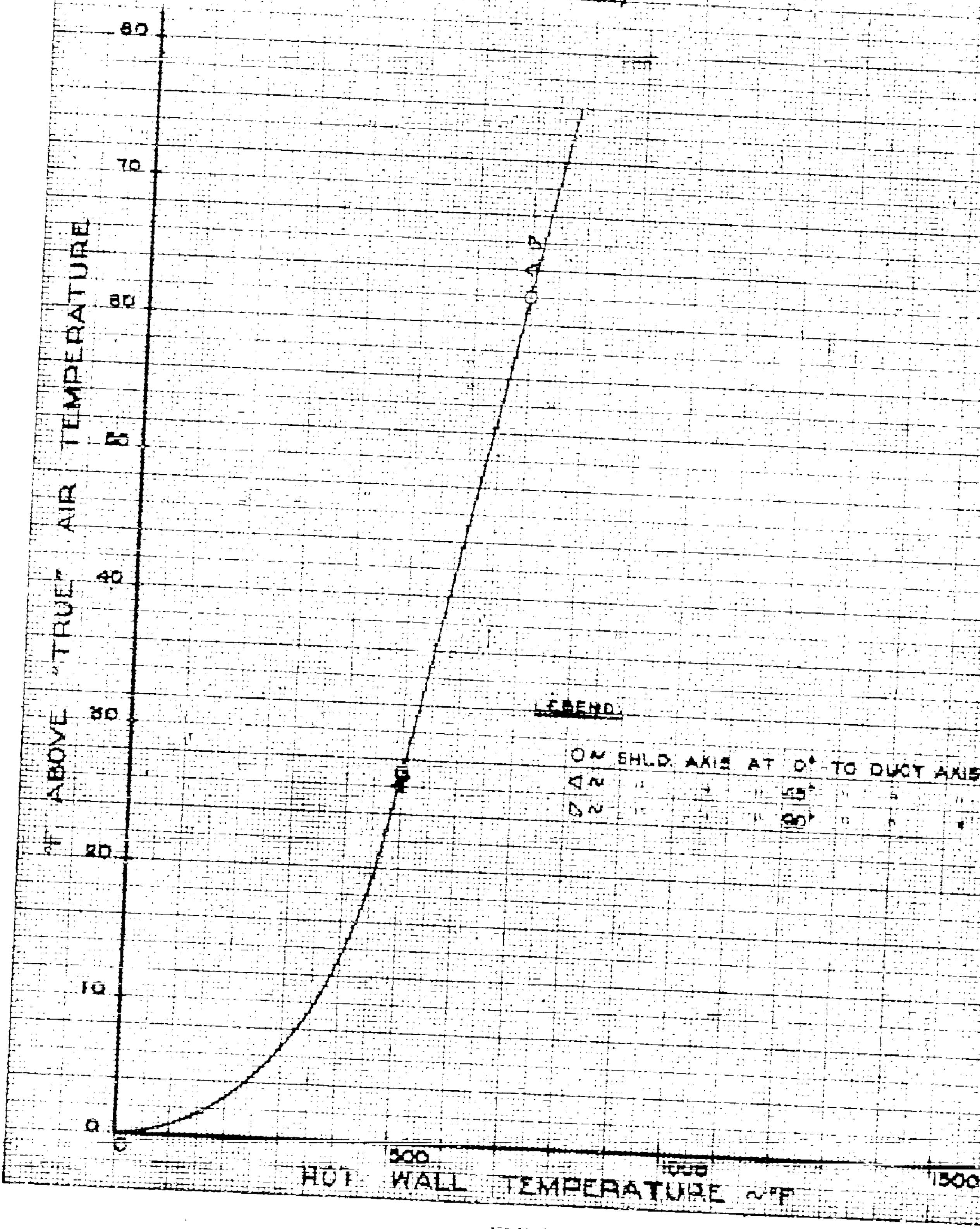

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FIG. 31: EFFECT OF ORIENTATION TO 45 LB-MIN⁻¹-FT⁻² FLOW ON TEST THERMOCOUPLE READING.
(HALF SHLD. SPECIMEN #9)

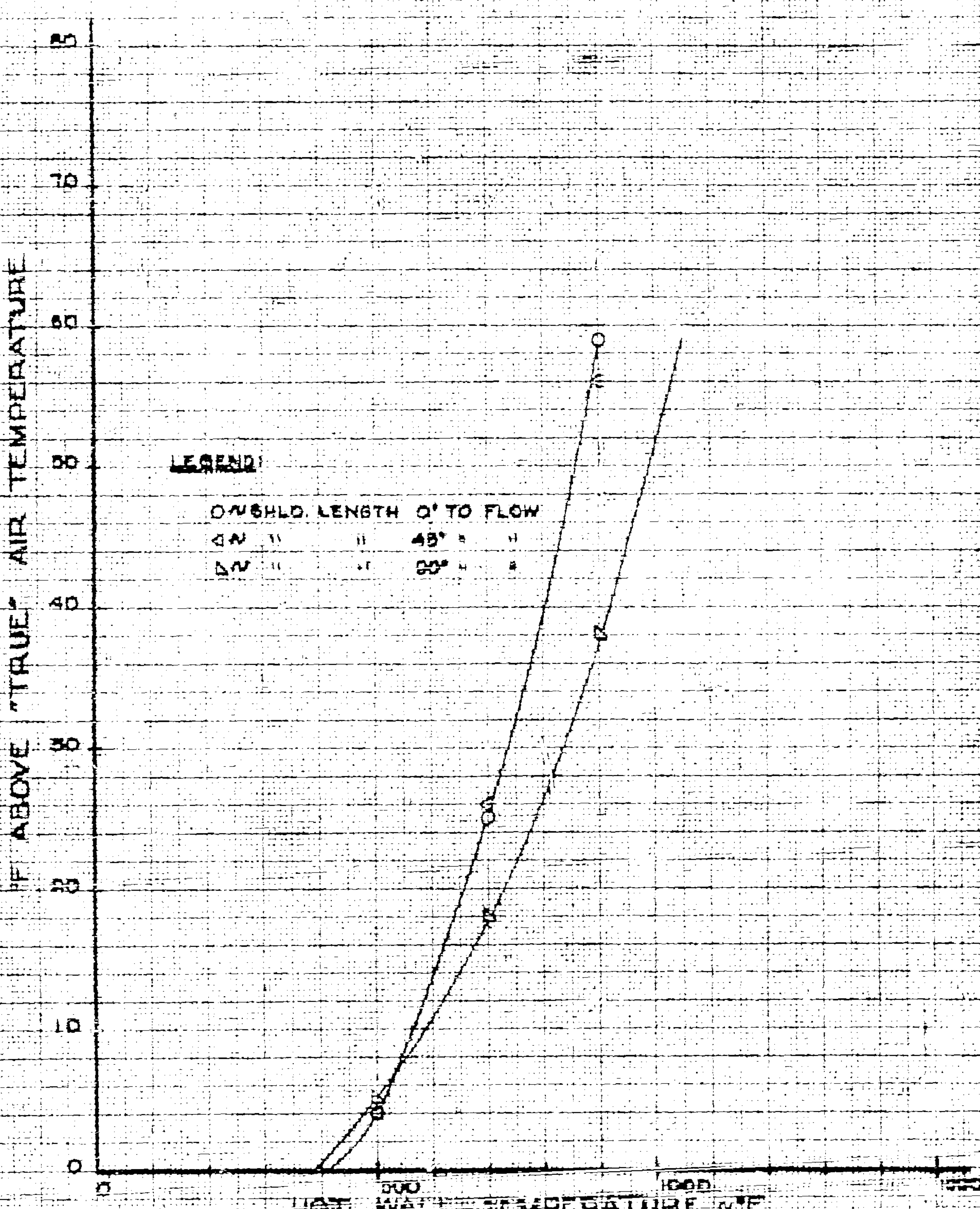

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FIG.50: EFFECT OF ORIENTATION TO 19LB-MIN^{-1}-FT^{-2} FLOW ON TEST THERMOCOUPLE READING (HALF SHLD SPECIMEN #9)

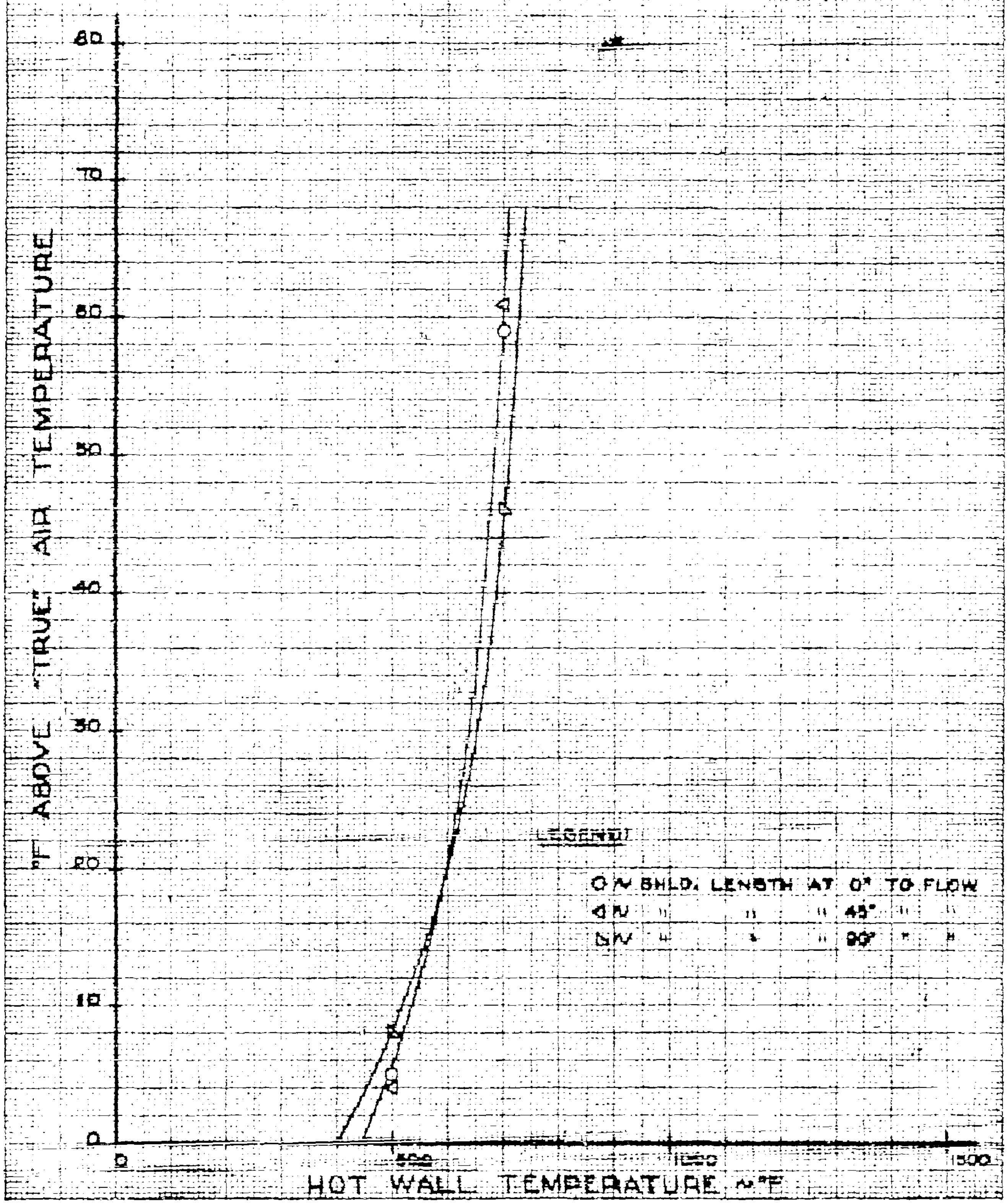

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FIG. 5K: EFFECT OF ORIENTATION TO [illegible] $LB-MIN^{-1}-FT^{-2}$ FLOW ON TEST THERMOCOUPLE READING
(HALF SHLD. SPECIMEN #9)

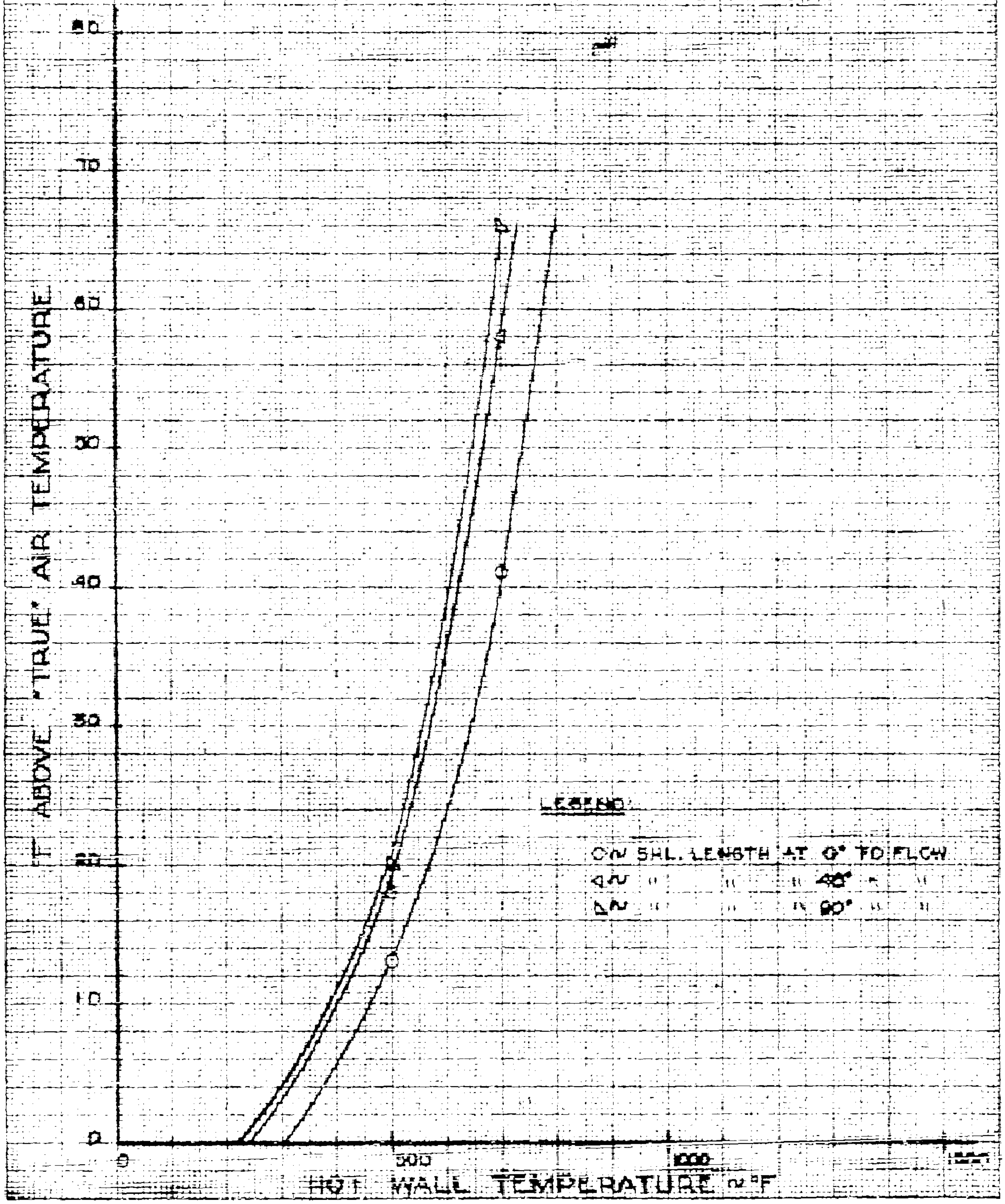

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FIG. 31: EFFECT OF ORIENTATION ON TEST THERMOCOUPLE READING AT ZERO FLOW. (HALF SHLD. SPECIMEN #3)

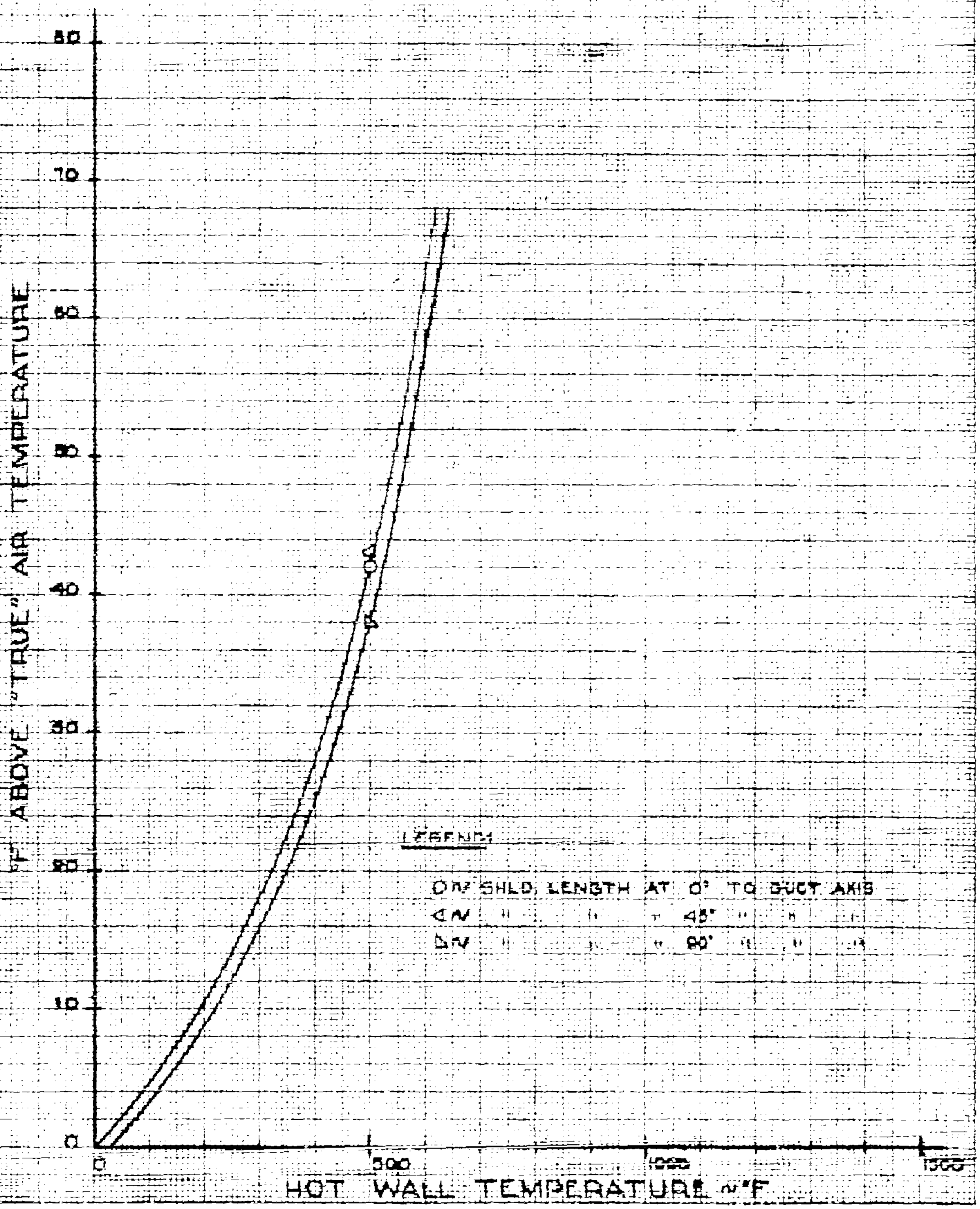

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FIG. 3M: EFFECT OF ORIENTATION TO 48LB-MIN⁻¹FT⁻² FLOW ON TEST THERMOCOUPLE READING.
(2"x2" UMBRELLA)

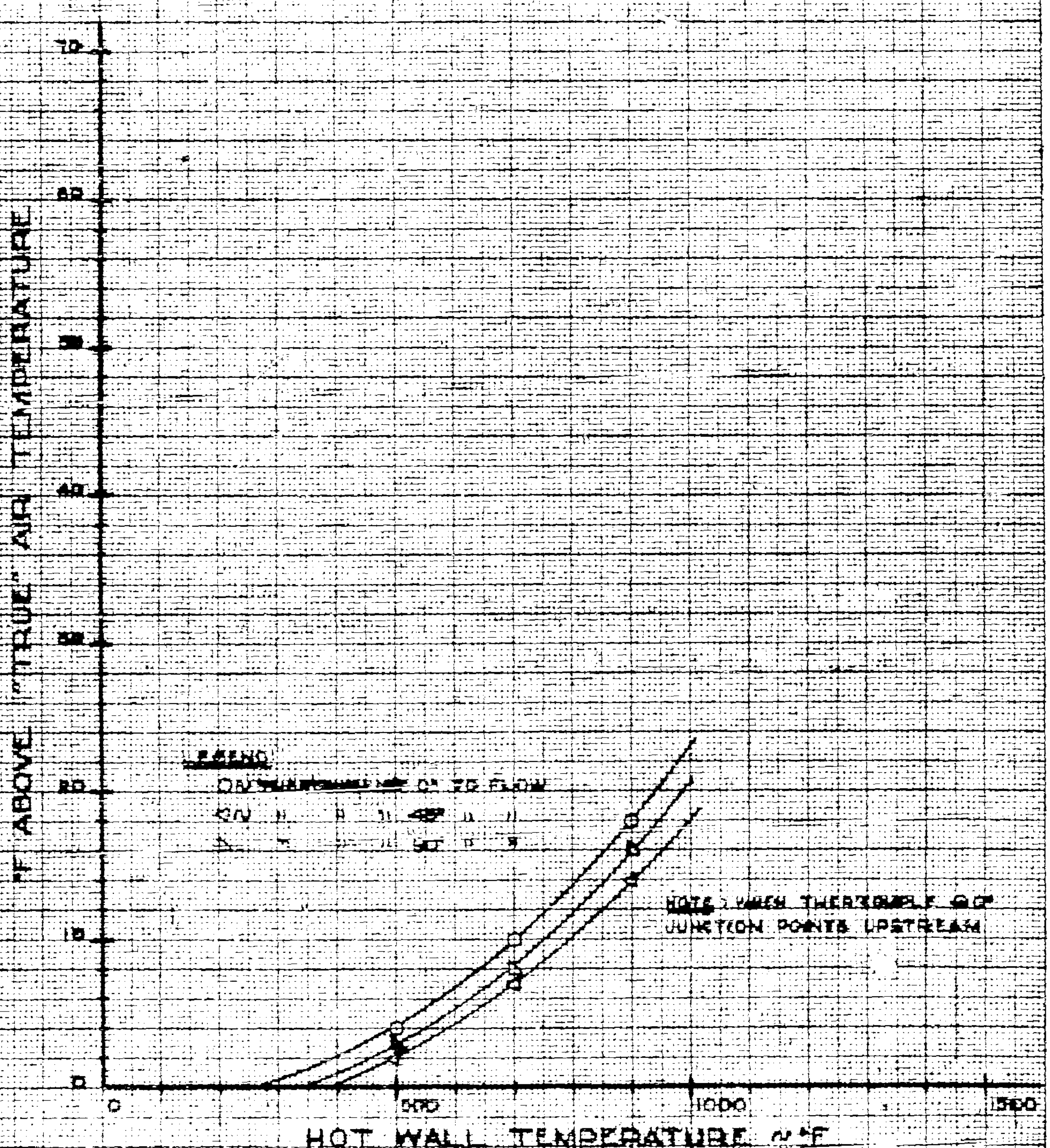

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FIG. 3N: EFFECT OF ORIENTATION TO 19 LB-MIN⁻¹-FT⁻² FLOW ON TEST THERMOCOUPLE READING
(2"×2" UMBRELLA)

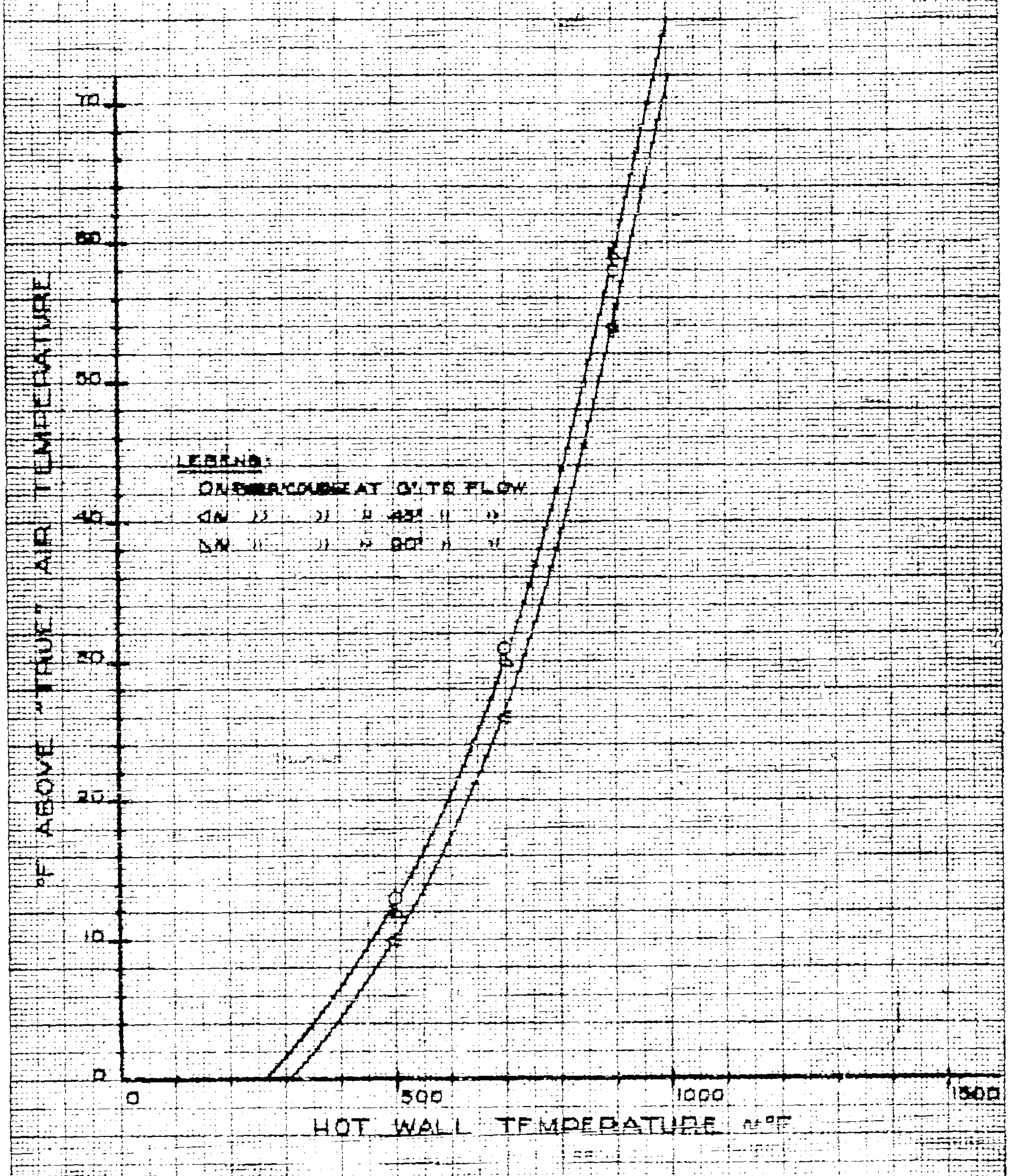

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FIG. 30: EFFECT OF ORIENTATION TO 9.6 LB-MIN-FT² FLOW ON TEST THERMOCOUPLE READING (2"x2" UMBRELLA)

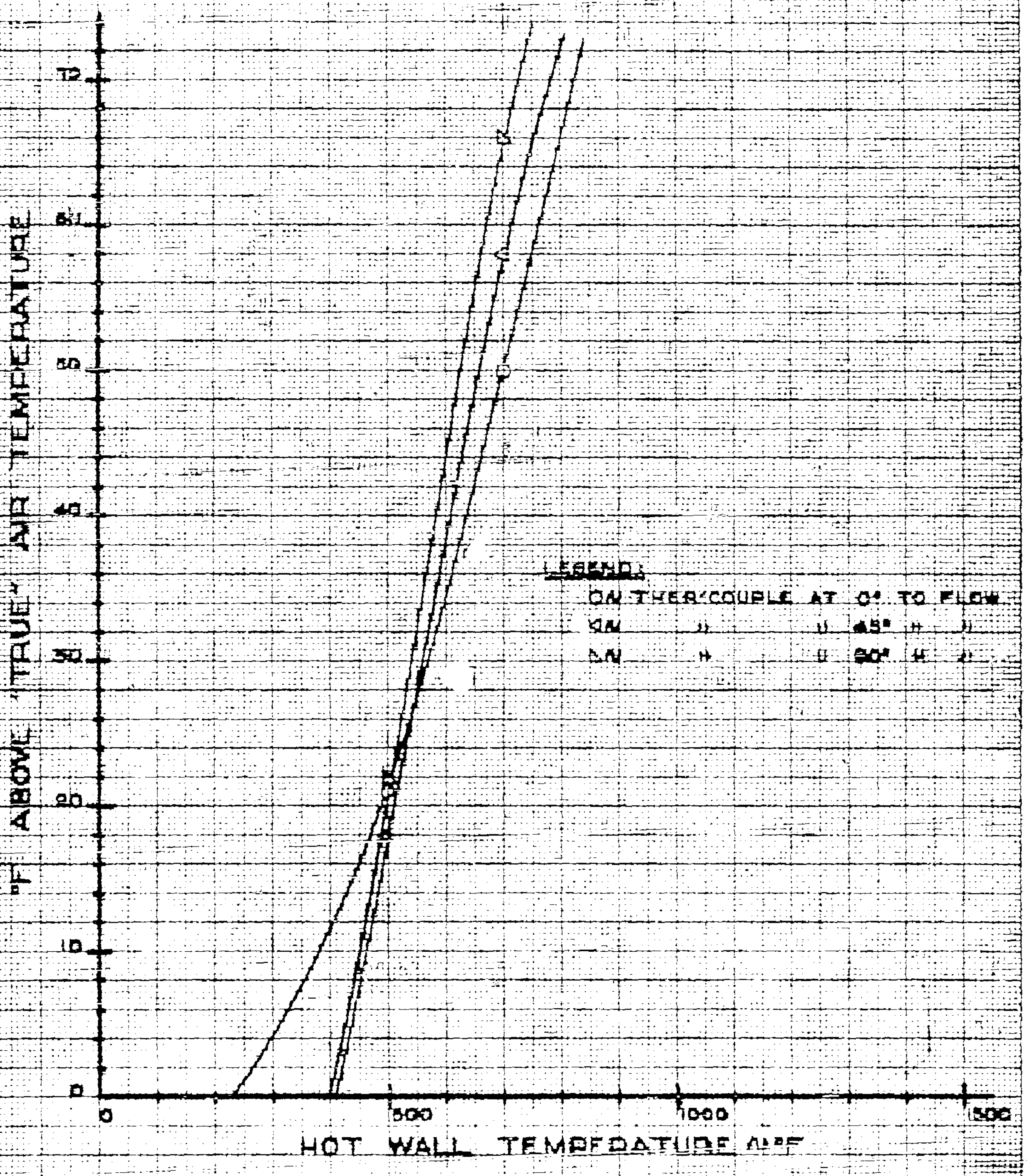

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FIG.38: EFFECT OF ORIENTATION ON TEST THERMOCOUPLE READING AT ZERO FLOW.
(2"×2" UMBRELLA)

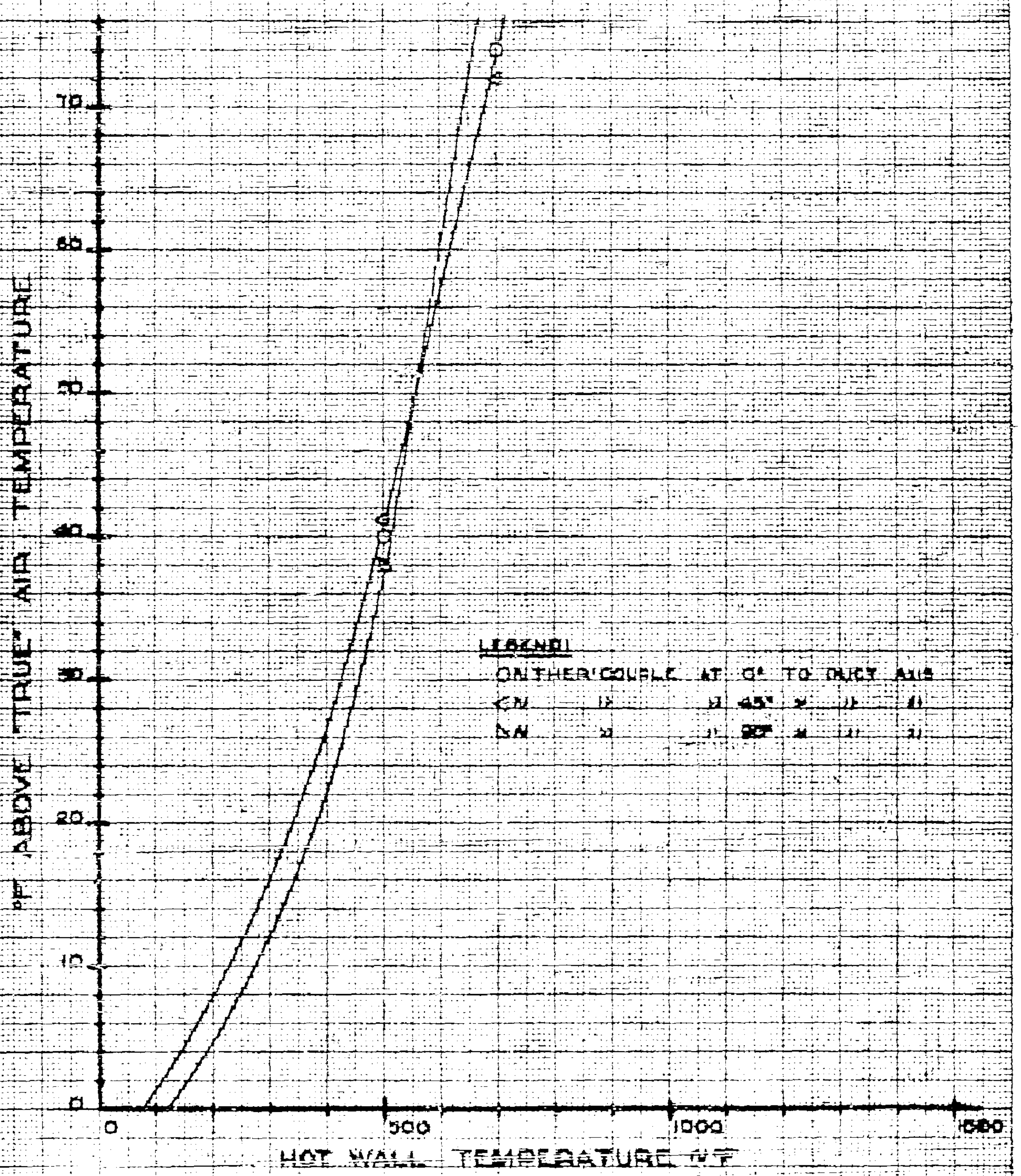

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FIG. 30: EFFECT OF ORIENTATION TO 48 LB-MIN⁻¹-FT⁻² ON TEST THERMOCOUPLE READING.
(2" INNER-3" OUTER-SHIELD)

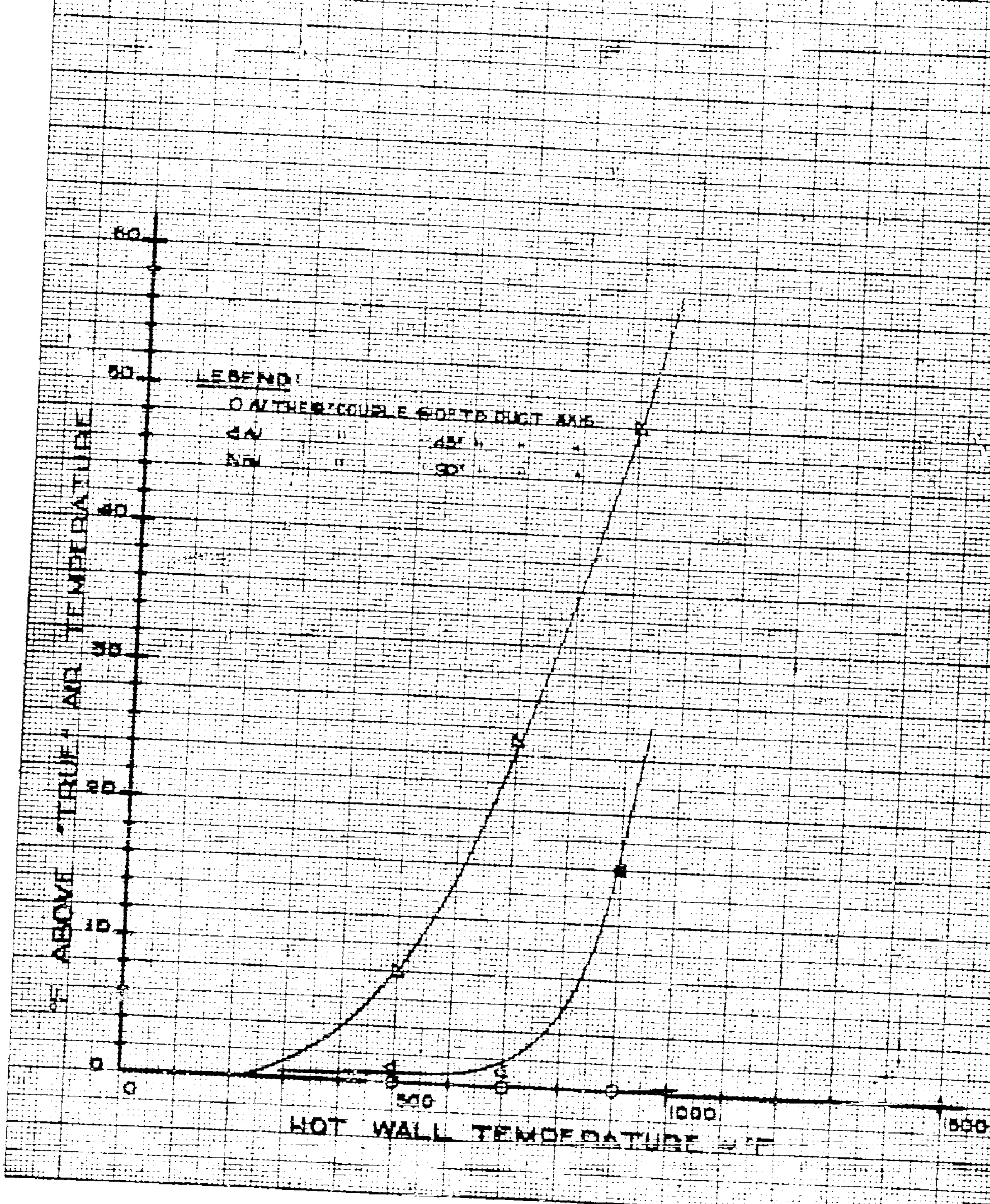

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FIG. 3R: EFFECT OF ORIENTATION TO 19 LB-MIN^{-1}-FT^{-2} ON TEST THERMOCOUPLE READING. (2" INNER-3" OUTER-SHIELD)

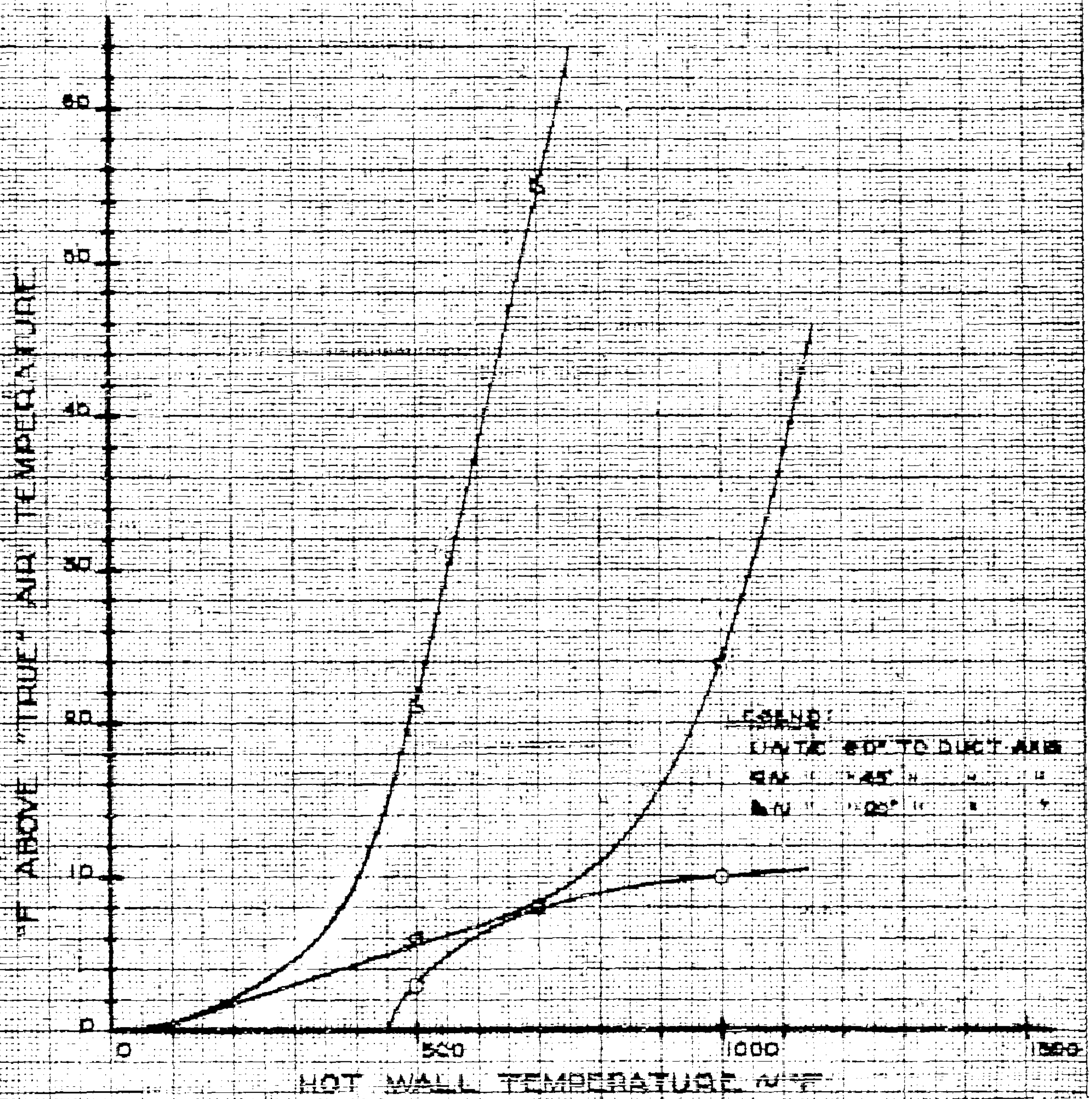

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FIG. 55 EFFECT OF ORIENTATION TO 8.0 LB-MIN⁻¹-FT⁻² ON TEST THERMOCOUPLE READING (2" INNER-3" OUTER-SHIELD)

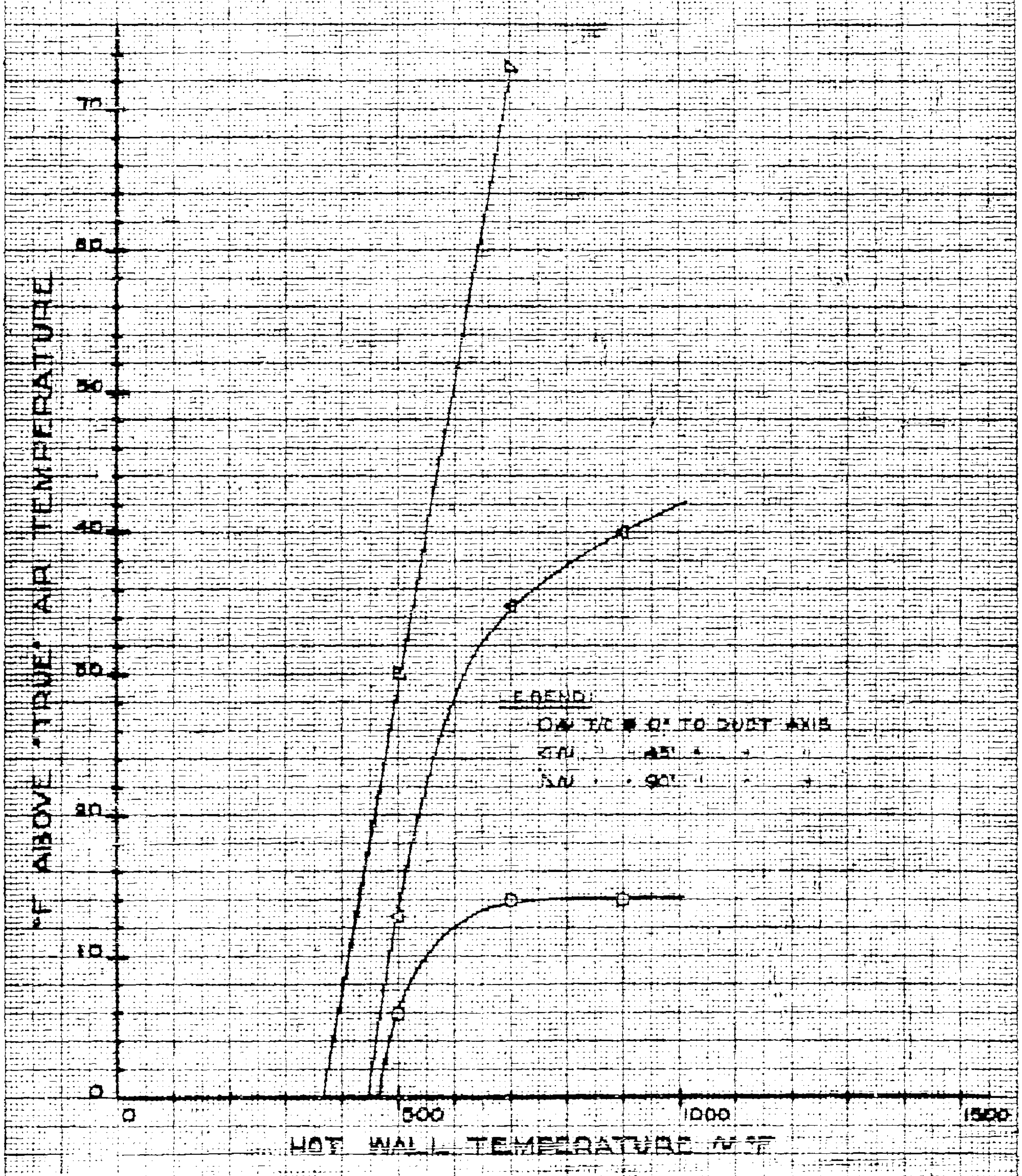

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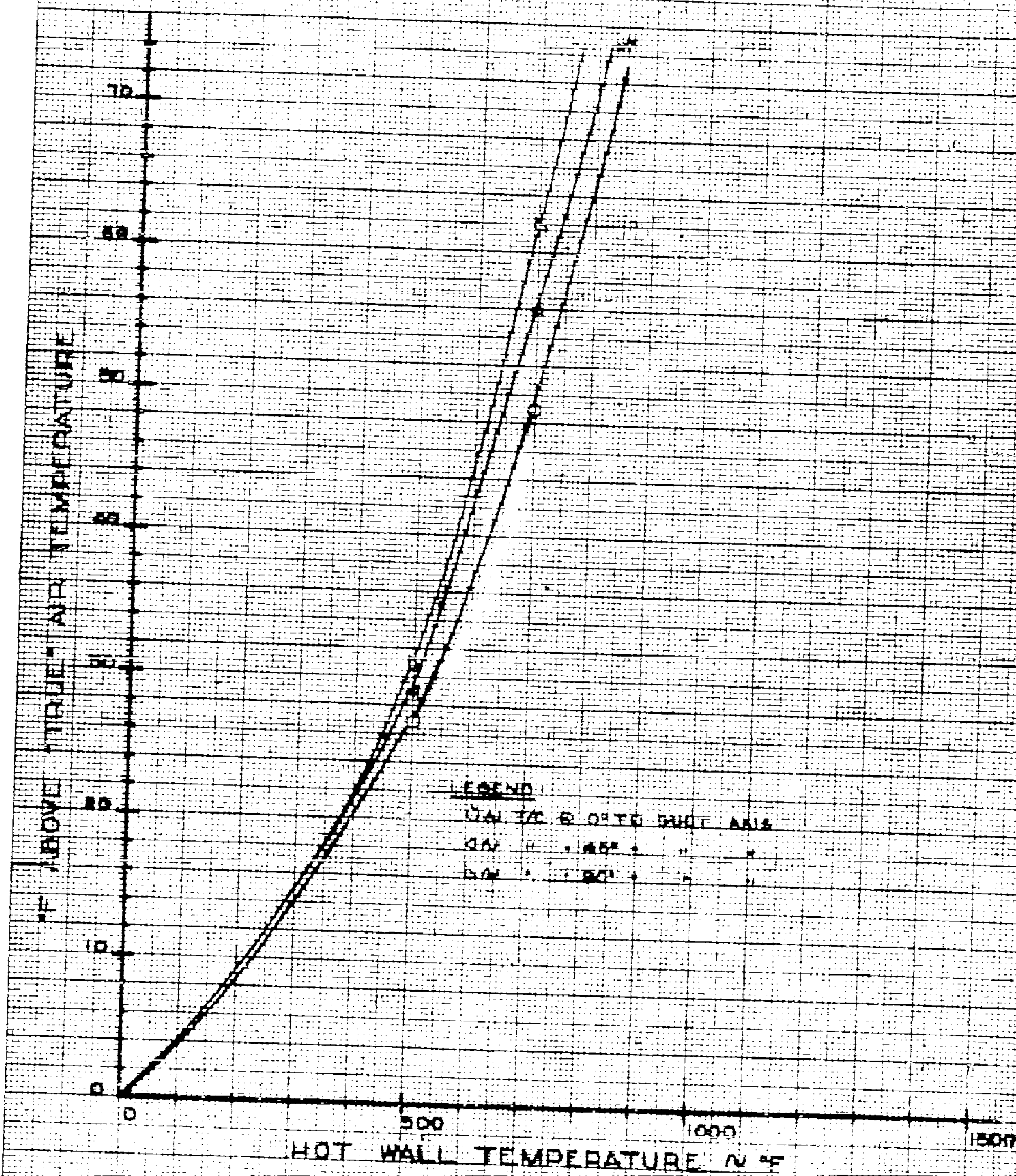
FIG. 37 EFFECT OF ORIENTATION ON TEST THERMOCOUPLE READING AT ZERO FLOW (2" INNER - 3" OUTER - SHIELD)



ENGINEER	NORTHROP AIRCRAFT, INC.	PAGE
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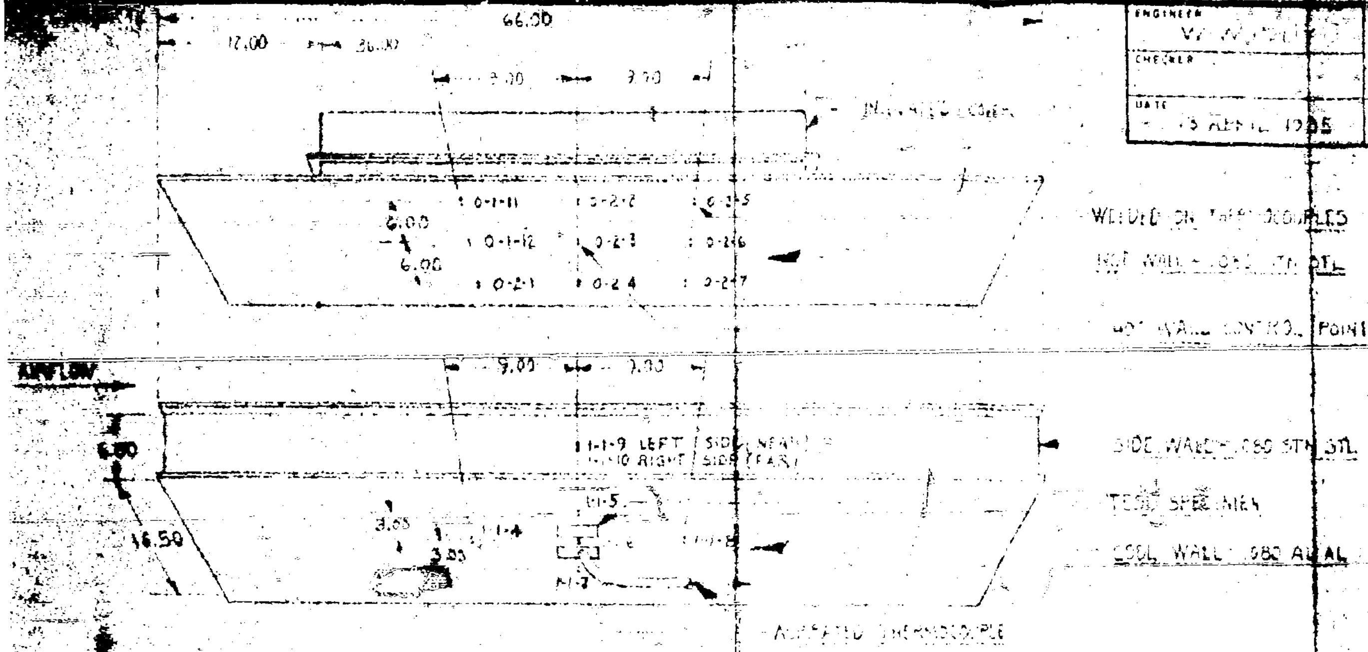
DATE 15 APRIL 1955	TYPICAL WALL TEMPERATURES	MODEL



Note: Airflow through the aspirated thermocouple affected the temperature of the specimen and thus required separate determination of specimen and aspirated thermocouple temperatures. Temperature stabilization was therefore first established for the specimen with the aspirator off (upper line) and second for the aspirated thermocouple with the aspirator on (lower line in table)

TABLE I REPRESENTATIVE TEST CHAMBER TEMPERATURES

	DUCT AIR		ASPIRATED	TEMPERATURES — DEGREES FAHRENHEIT																
							HOT WALL						SIDE WALL		COLD WALL					
[illegible]	FLOW PPM	INLET TEMP-F	THERMO-COUPLE	0-1-11	0-1-12	0-2-1	0-2-2	0-2-3	0-2-4	0-2-5	0-2-6	0-2-7	1-1-9	1-1-10	1-1-4	1-1-5	1-1-6	1-1-7	1-1-8	[illegible]
[illegible]	30	74	OFF	345	333	351	481	509	484	[illegible]	425	481	99	105	97	105	99	105	107	80
		74	ON	349	336	352	432	501	485	461	432	482	100	104	98	106	100	106	109	81
	12	71	OFF	370	361	368	492	500	438	458	439	490	118	121	115	126	121	129	129	76
		72	ON	368	360	374	492	502	500	458	441	490	119	122	116	126	121	129	130	[illegible]
	6	72	OFF	400	394	400	512	500	489	483	468	471	126	128	127	137	134	140	140	73
		72	ON	402	396	403	514	508	484	481	463	465	127	128	127	137	133	139	139	73
	0	—	OFF	435	435	422	509	500	478	462	442	443	136	136	137	138	139	138	137	[illegible]
		—	ON	434	434	424	499	498	476	462	441	442	135	133	135	137	137	137	136	[illegible]
700 F	30	71	OFF	525	511	542	681	700	675	653	609	685	129	142	130	143	134	151	152	76
		71	ON	525	511	543	681	701	696	655	610	689	131	143	130	141	132	149	151	75
	12	70	OFF	551	550	564	695	700	700	655	620	685	164	168	164	186	175	184	188	79
		70	ON	553	550	565	698	703	702	656	622	687	166	172	165	186	175	184	190	79
	6	74	OFF	609	599	613	718	710	692	673	649	665	182	184	186	203	198	208	205	80
		74	ON	611	600	617	720	709	698	673	647	664	182	185	187	203	196	207	206	78
	0	—	OFF	630	635	628	704	700	682	653	632	648	198	196	215	220	212	214	207	83
		—	ON	630	634	[illegible]	702	[illegible]	679	655	630	644	194	194	212	217	207	211	205	82
900 F	30	63	OFF	728	708	750	879	899	898	853	792	880	190	218	199	229	209	236	238	83
		63	ON	729	708	750	880	899	898	855	794	880	190	218	200	229	209	237	238	83
	12	74	OFF	797	776	813	931	900	925	852	809	897	254	266	267	299	285	310	298	78
		74	ON	798	777	814	934	902	929	865	812	899	255	271	269	300	284	310	297	78
	6	72	OFF	832	829	837	931	901	911	880	837	872	254	258	263	290	284	300	292	[illegible]
		72	ON	834	823	841	931	909	914	879	833	870	255	260	265	290	278	298	293	[illegible]
	0	—	OFF	829	838	837	900	900	882	852	828	843	279	279	310	320	313	315	[illegible]	[illegible]
		—	ON	831	842	835	900	896	882	852	830	848	275	272	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

ENGINEER C. K. GORDON JR. CHECKER	NORTHROP AIRCRAFT, INC.	PAGE 65 REPORT NO. NAI 55-278
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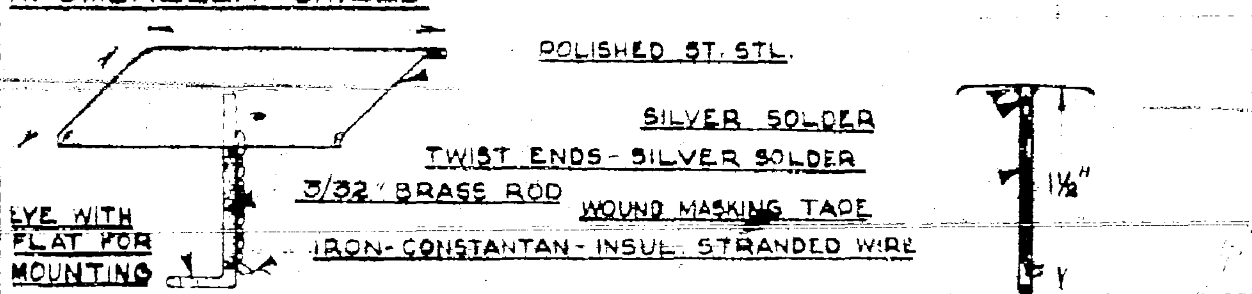
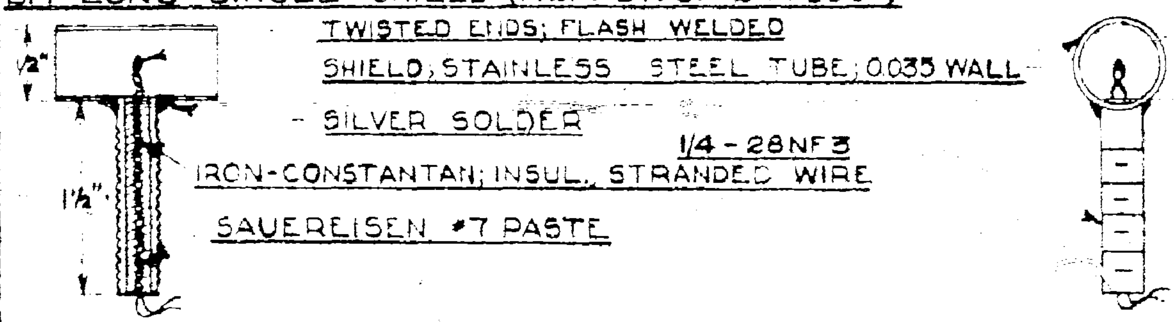
A. UMBRELLA SHIELD

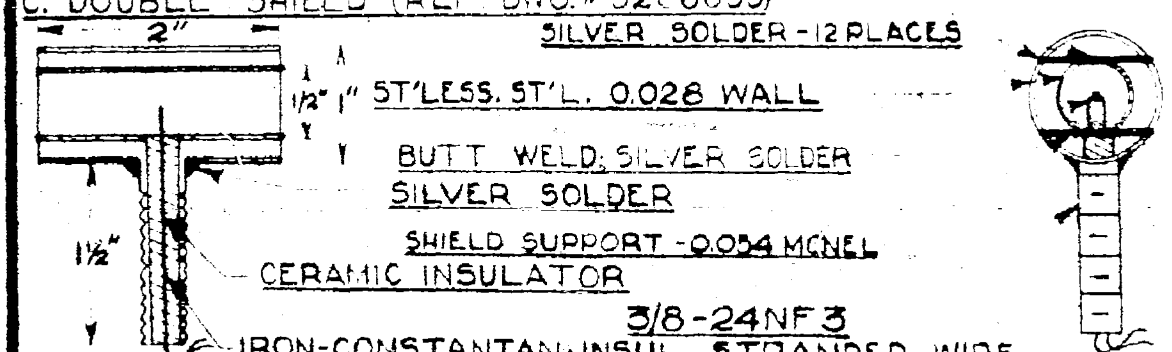


B. 1" LONG SINGLE SHIELD (REF. DWG. #2005591)

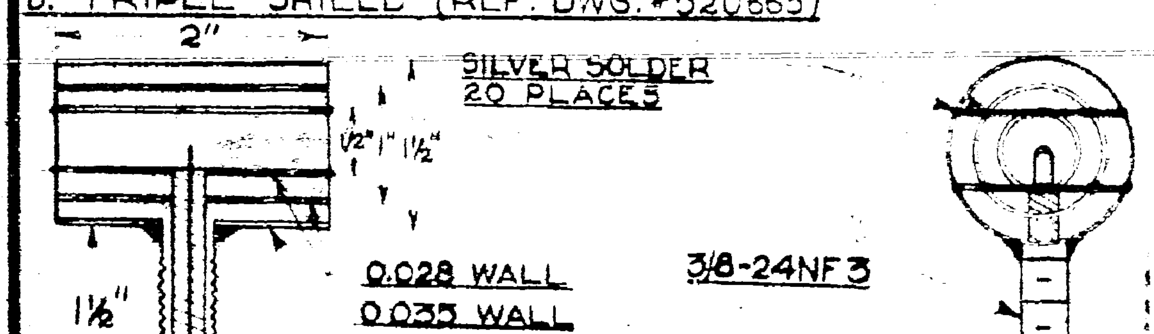


NOTE: 2" LONG SPECIMEN SAME EXCEPT SHIELD HAS 0.028 WALL AND STEM CONTAINS 2-HOLE CERAMIC INSULATOR (REF. DWG. #5206655).

C. DOUBLE SHIELD (REF. DWG. #5206655)



D. TRIPLE SHIELD (REF. DWG. #520665)



NOTE: DETAILS OF CONSTRUCTION SAME AS SPECIMEN "C".

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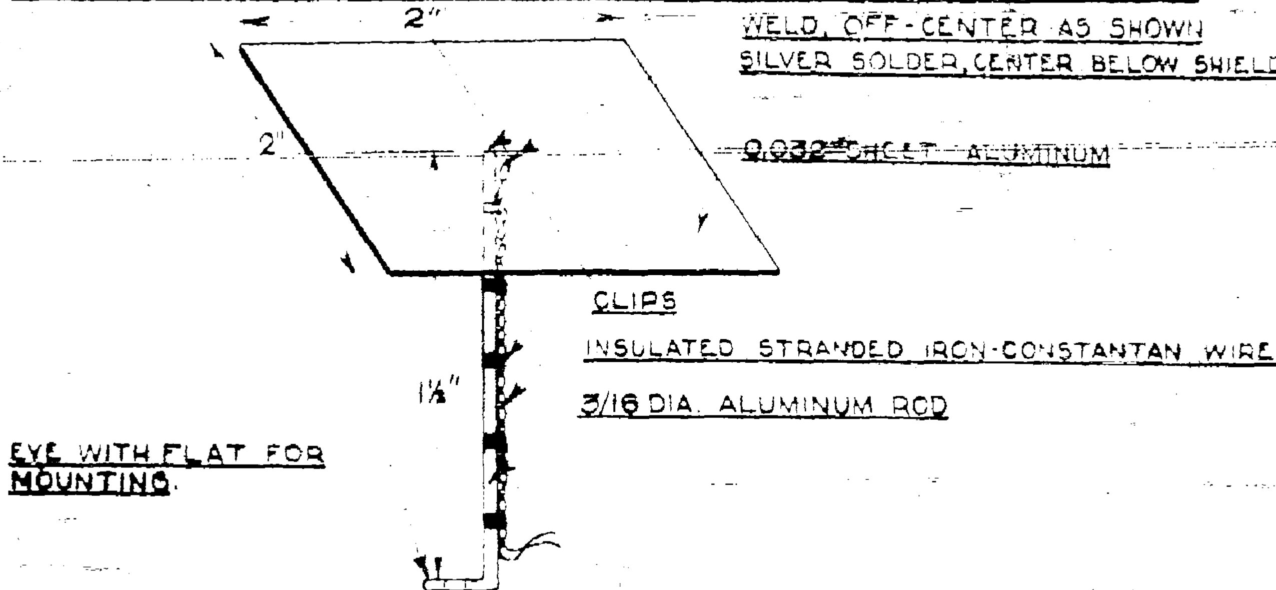
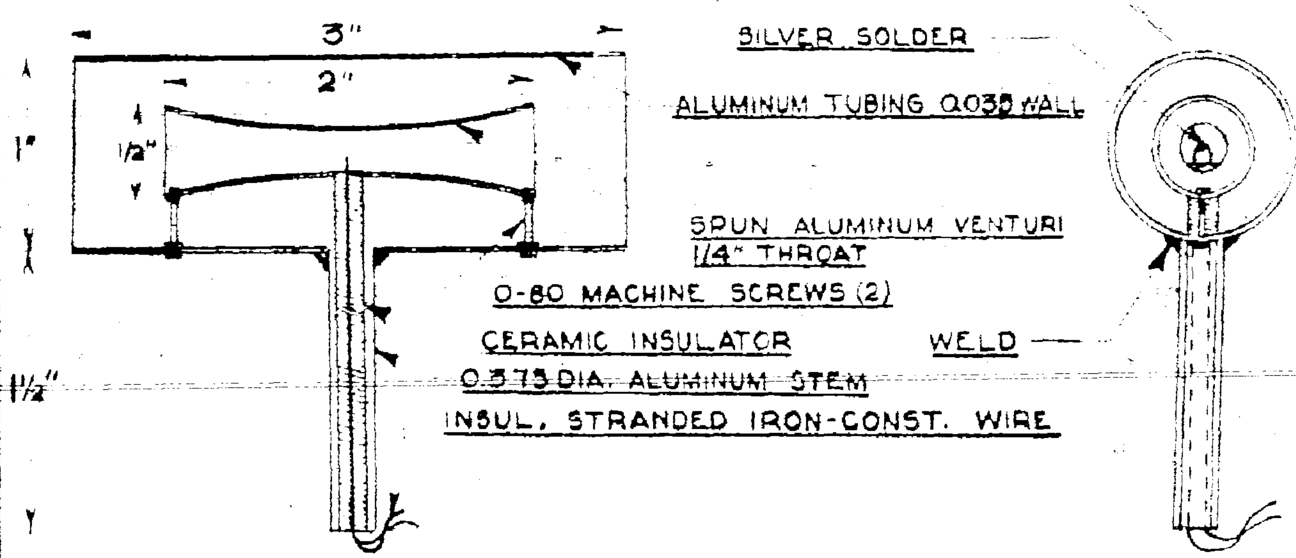
E. FLAT UMBRELLA SHIELD (REF. DWG. #5206959)



NOTE: ONE ADDITIONAL, EXACTLY AS ABOVE AND WITH 2×2", 1/16" THICK SHEET ASBESTOS COVERED WITH ALUMINUM FOIL.

F. VENTURI DOUBLE SHIELD (REF. DWG. #5206959)



FORM 55-7A (R. 9-51)

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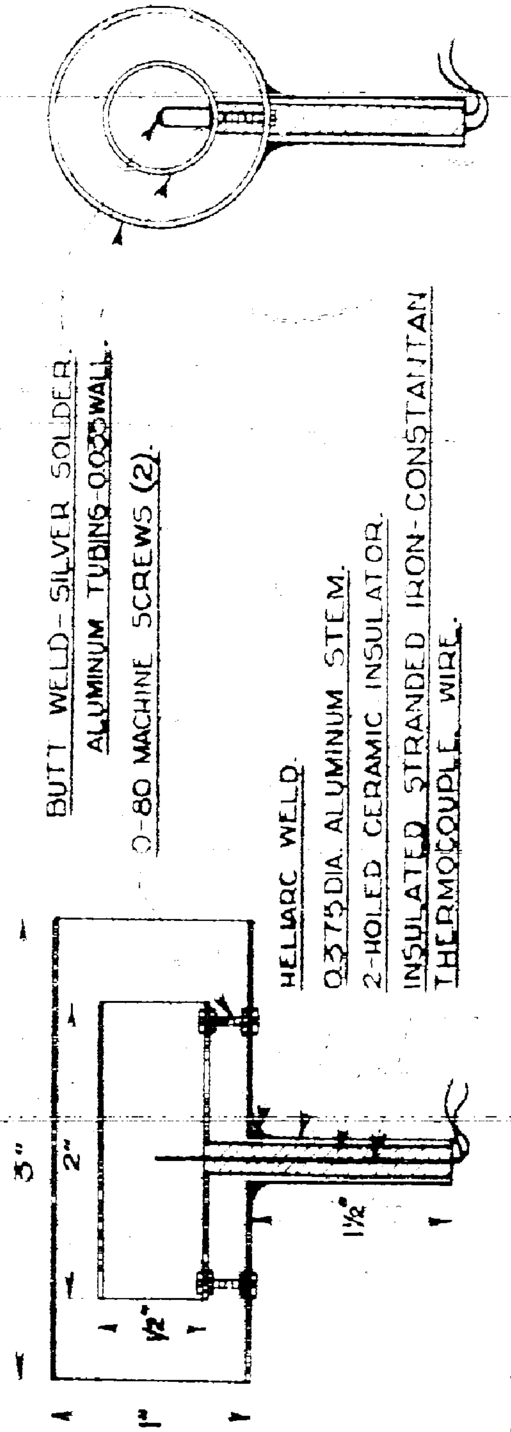
G. 3" OUTER-2" INNER-DOUBLE SHIELD



REF. DWG. #3208959

FORM 80-7A (R. 9-51)

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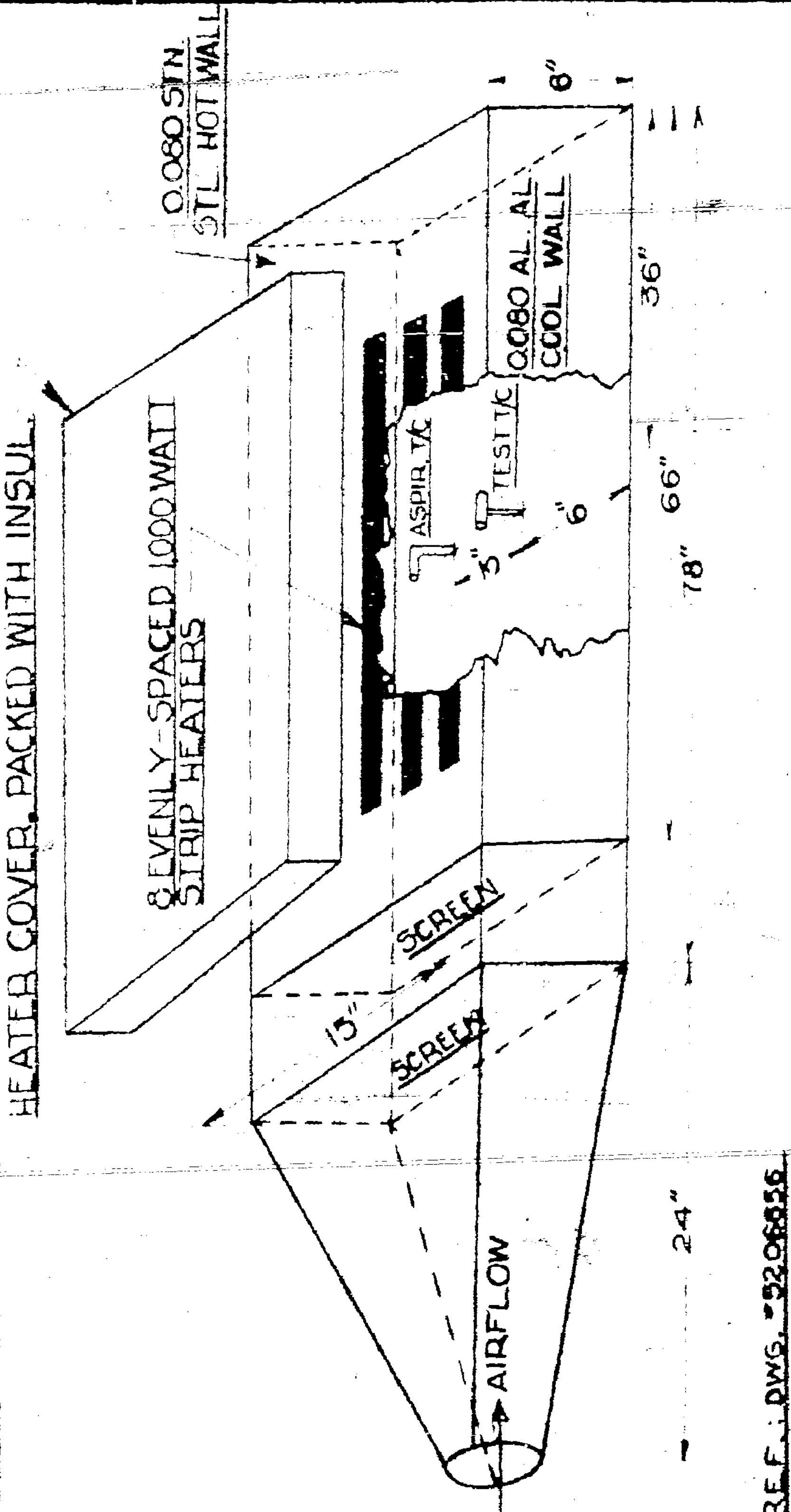

FIG. 5: TEST CHAMBER

FORM 80-7A (R. 8-51)

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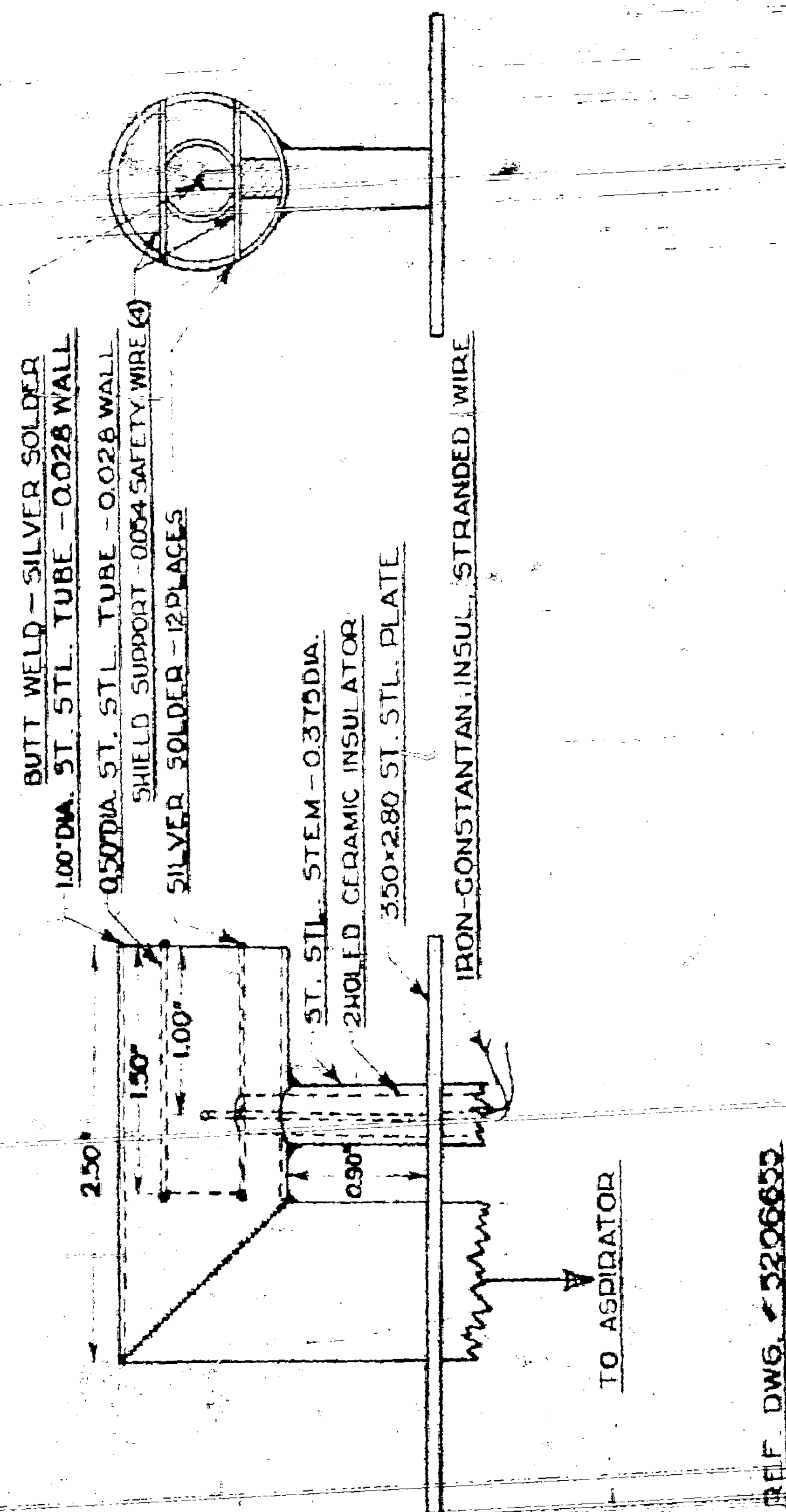
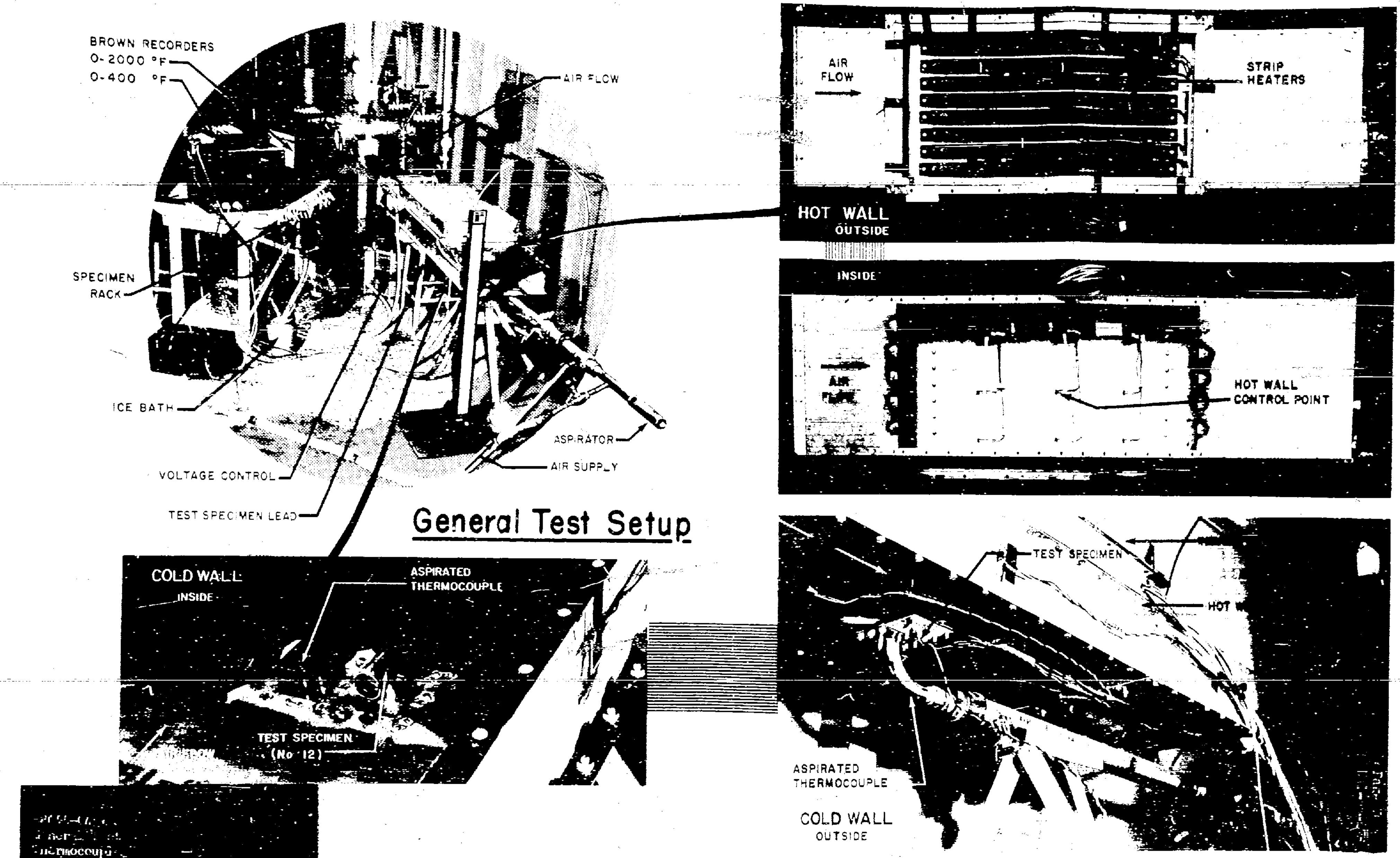
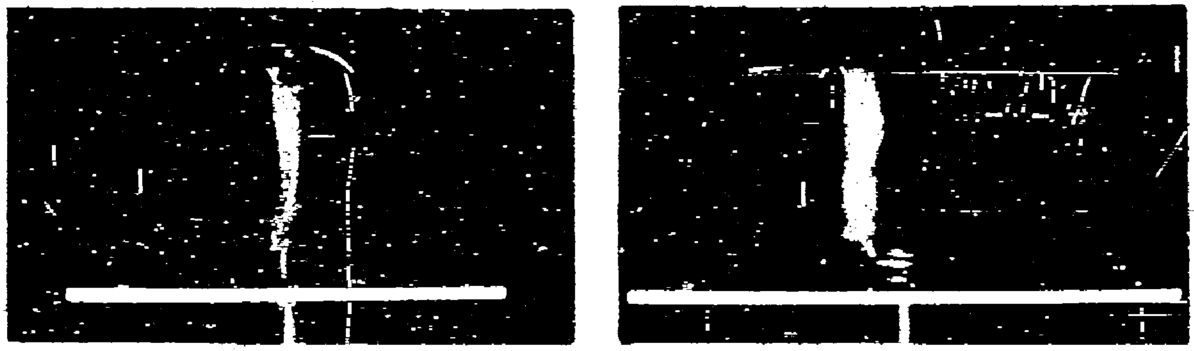
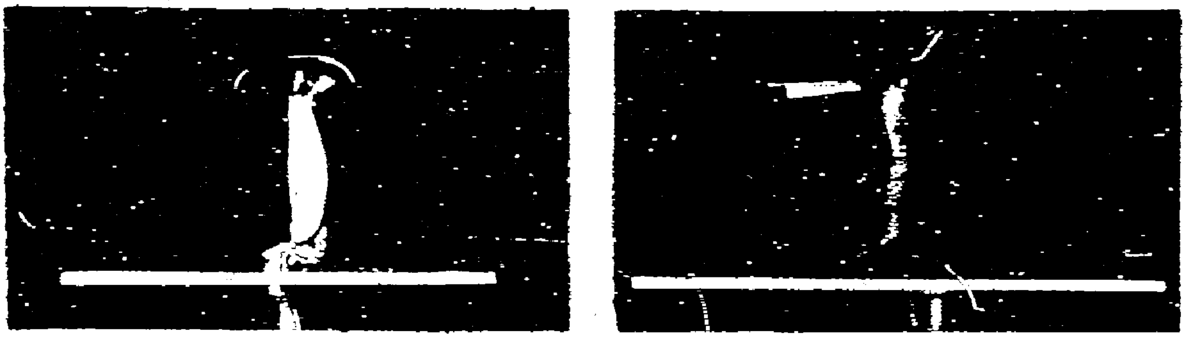




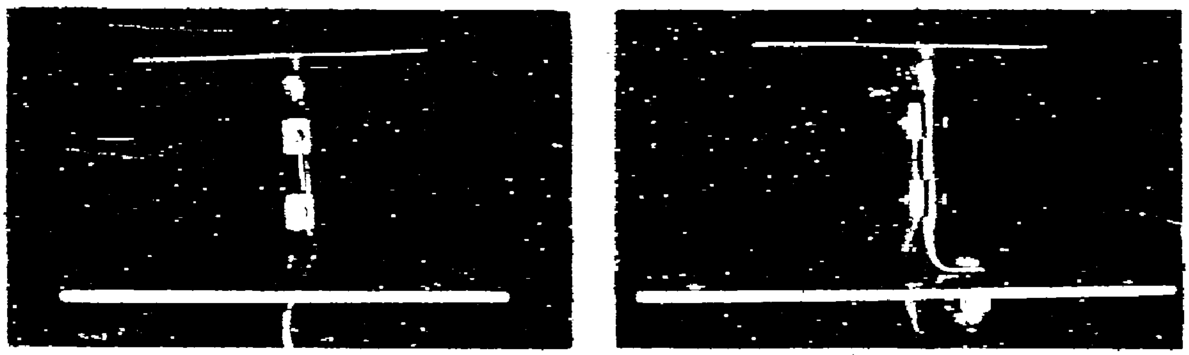
General Test Setup



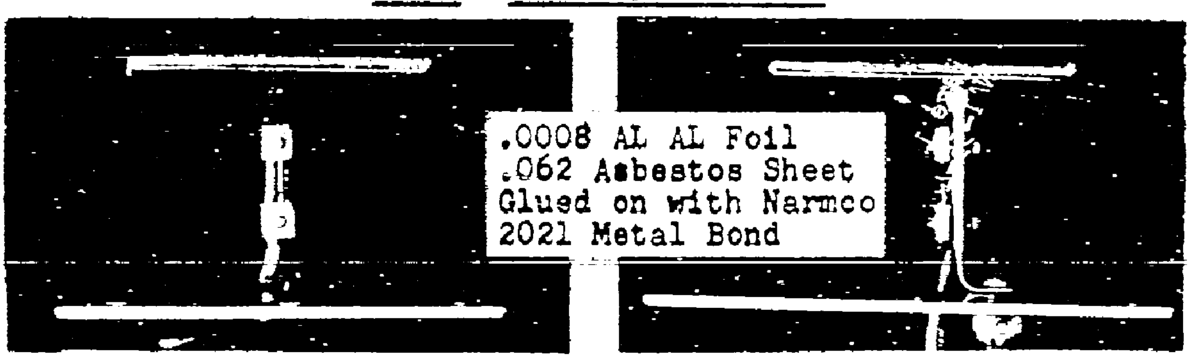
No 8- 1.00 SQUARE STN STL No 1



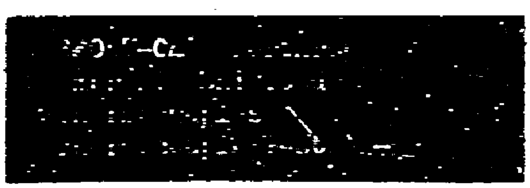
No 9- 1.00 SQUARE STN STL No 2



No 10- 2.00 SQUARE AL AL

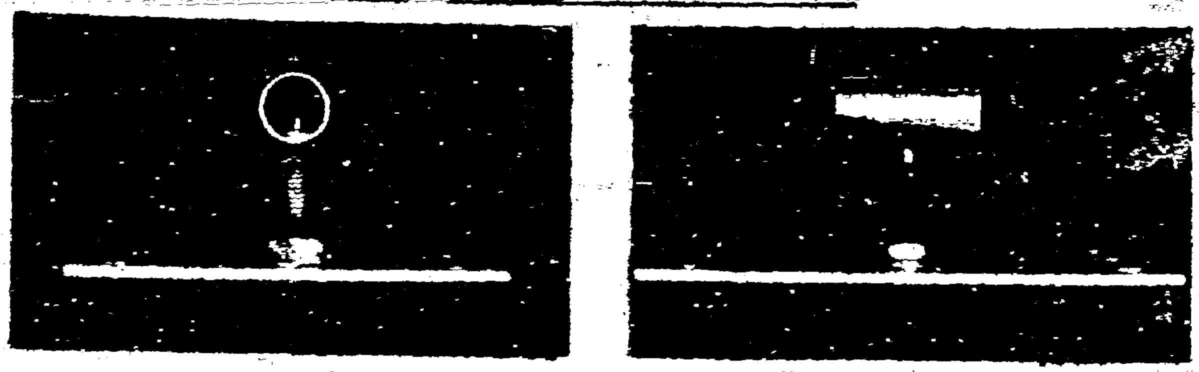


No 11- 2.00 SQUARE AL A



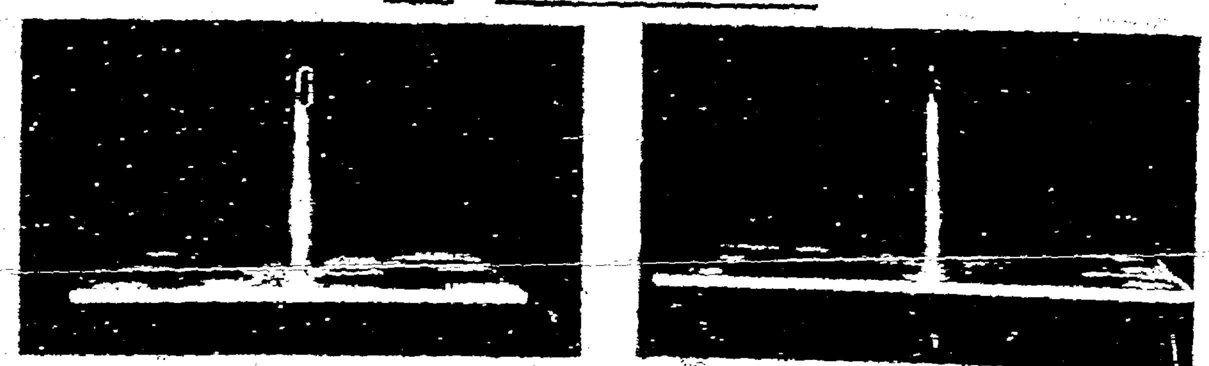
(Similar to No 10 except as noted)

No 1- 1.00 LONG STN STL No 1

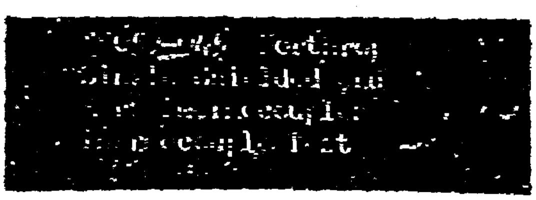


No 2- 1.00 LONG STN STL No 2

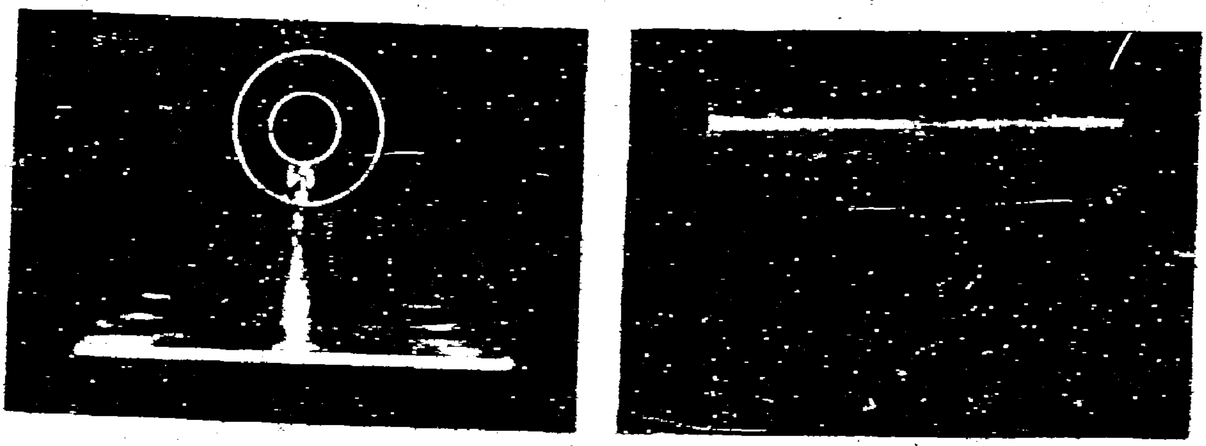
No 3- 2.00 LONG STN STL



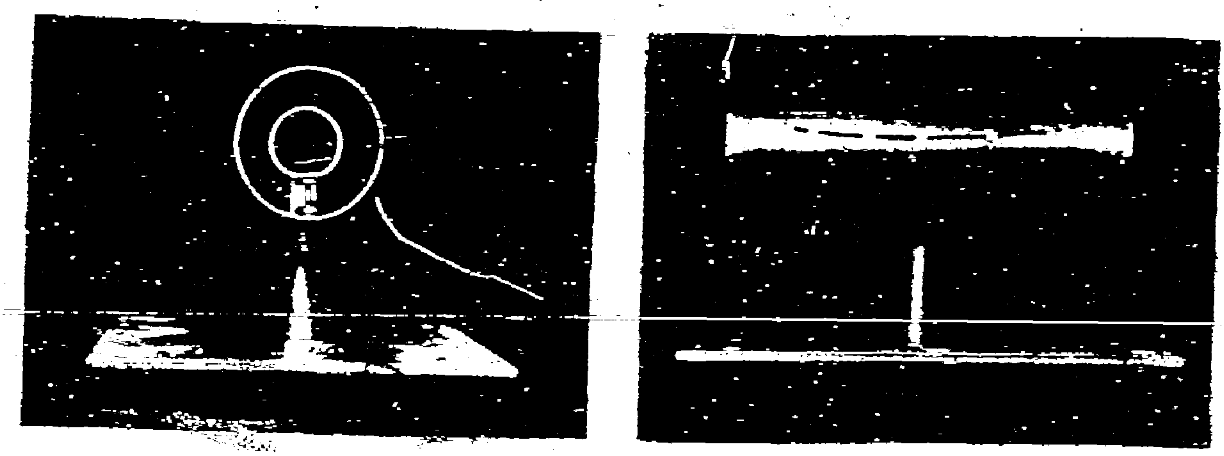
No 7- BARE



No 4- 2.00 LONG STN STL



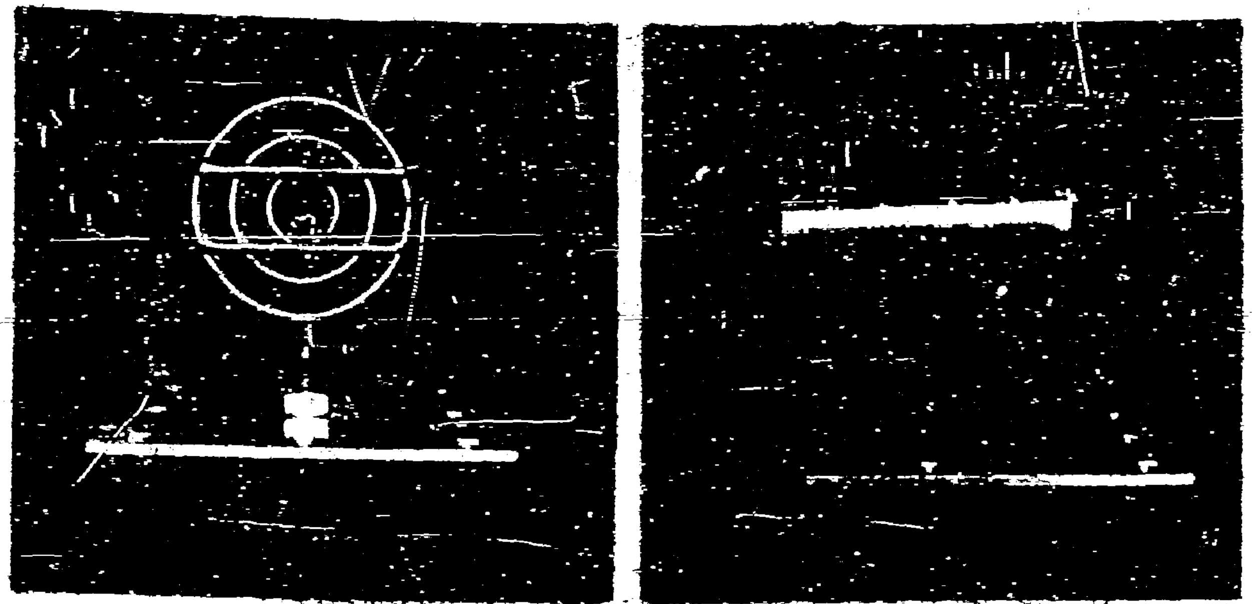
No 12- 3.00 LONG AL AL



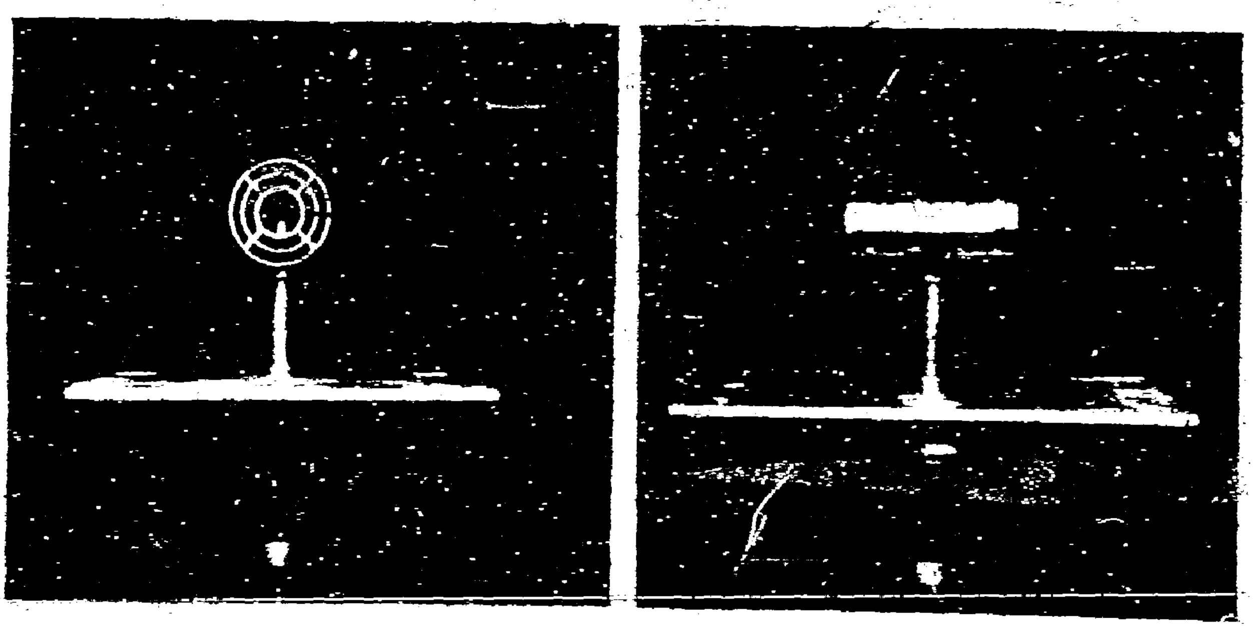
[illegible]-45 Venturi
Double [illegible]
Thermocouples
Thermocouple [illegible]

No 13- 3.00 LONG AL AL

(Venturi)

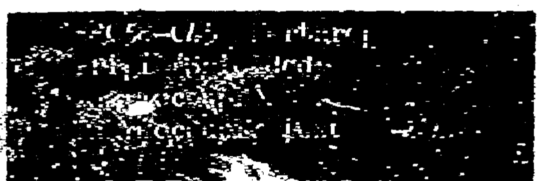


No 5- 2.00 LONG STN STL



No 6- 1.25 LONG STN STL

(Revere Corp)



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